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Eighth Semiannual Technical Report

March 1977

For the Project

INTEGRATED DOD VOICE & DATA NETWORKS
AND GROUND PACKET RADIO TECHNOLOGY

VOLUME 2

COST TRENDS FOR LARGE VOLUME
PACKET NETWORKS

network analysis corporatio

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INTEGRATED DOD VOICE AND DATA NETWORKS AND GROUND PACKET RADIO TECHNOLOGY

VOLUME 2

COST TRENDS FOR LARGE VOLUME PACKET NETWORKS

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LARGE SCALE PACKET SWITCHED NETWORK DESIGN TRADEOFFS

6.1 INTRODUCTION

Previous NAC data network studies ([NAC, 1975], [NAC, 1976]) have revealed the fundamental properties and relative costs of a variety of network architecture alternatives. The cost comparisons were made with a constant backbone subnet average end-to-end delay - a crucial performance parameter. Complex line cost structures were created to accurately model existing and projected tariffs.

This study focuses on the packet-switched network approach with all users fully integrated in an overall facility sharing plan. Simplifying assumptions are made throughout so that fundamental design decision tradeoffs can be revealed and so that the sensitivities to cost trends brought about by new technologies can be assessed. In particular, the effects of the following anticipated developments are exposed:

- Use of satellite transmission.
- Different switch capabilities.
- Altered ratio of processor cost to transmission line cost.

This study also extends the results of previous work by dealing with much higher traffic throughput volumes - 1.8 MBS to 180 MBS -and by using a more accurate data base of anticipated military data message traffic than was previously available.

6.2 THE NETWORK MODEL

The network model assumes that users in the same physical location merge their traffic with modem sharing units (MSU's), terminal control units (TCU's), multiplexers, concentrators, or some combination of these devices so that the entire data stream in and out of a location appears as a single stream to the network. Thus computer and terminal traffic, and traffic belonging to different systems are summed indifferently for each site to create a single lumped external data I/O requirement. In practice, any site where such a merge would be impractical or inadvisable could opt to have separate multiple access facilities and incur the additional cost with minimal consequence to other network users. Thus for the model used in this study, all configuration considerations within a facility are ignored. The data base contained instances of facilities that were separately identified but had geographic coordinates indicating colocation. These facilities were treated as separate data streams, but in cases where telecommunication connections were required between them, no cost was assigned.

The network architecture adopted for this study of packet switching network costs is a three-tiered hierarchical system. As already mentioned, at the hierarchy level closest to the user, an optimal local site configuration is assumed so that the data traffic into and out of the site appears to the network as a single stream. At the hierarchy level furthest from the user, a backbone network provides high interconnection, good utilization of generally high bandwidth links, alternate paths for throughput improvement (through routing optimization) and reliability. To insure adequate backbone reliability at least two node disjoint paths are provided between all points in the backbone network, except for some designs which used satellite links.

An intermediate hierarchy level, called concentration, is introduced between the local sites and the backbone network. These intermediate devices are generically called concentrators, but in practice may be concentrators, multiplexers, or statistical multiplexers according to cost/performance requirements. Their function is to collect the traffic from a regional group of sites and lump it into a single channel, thus reducing the costs for these sites to access the backbone subnet.

The concentrators were assumed to be limited to a throughput of 230 KBS - so they function only to merge the traffic streams of relatively small volume sites. Consequently their use diminishes as traffic volumes are scaled up. They serve to reduce the influence of the smaller volume sites on the overall network strategy. Higher throughput concentration points are not viable because of reliability considerations and also because the additional cost of installing a full backbone switch is small.

Sites are connected directly to a backbone switch or in some cases go through a concentrator to the backbone switch - both star or centralized configurations. Multipointing was not permitted since this would presume a collection of sites willing to operate at a common speed and discipline and willing to surrender their independent control of the local access portion of their end-to-end connections. Multipointing would also give diminished and unequal reliability to the served sites.

Since we are dealing with high traffic levels, the throughput requirements in the backbone network lead to high capacity lines - and consequently low transmission delays - in the backbone portion of an end-to-end connection. For the traffic levels considered here, these backbone delays are generally far below any interactive or other real-time data requirements. The delays in the local access portions may be more substantial, particularly for low speed access lines.

Since no information was available on the delay performance

requirements for the users at each site, by using the star configuration, no assumptions had to be made. Each site directly connected to a backbone switch can, in practice, upgrade its access line without impacting any other feature of the design. Sites that are connected to a concentrator, on the other hand, share the use of the concentrator-to-backbone connection. However the delay encountered over this second leg of the local access is usually a small fraction of the total local access delay; so here again, the individual user is in substantial control of his delay performance.

By the same logic, users requiring isolation from the common data stream, for any reason, can build separate access facilities and incur the extra cost without influencing the remainder of the design (except port facilities). If this practice became widespread, however, it would influence the optimal number and location of backbone and/or concentration facilities and cause a general increase in network costs - a result of trying to reduce the cost burden of the special access requirements. This accommodation cost would be an implicit part of the global network design cost and would be difficult to apportion to individual special access users.

Sites accessing the network through a concentrator do suffer some diminished reliability compared to users with direct backbone access. Even if relative equipment reliability is not an issue, the backbone nodes have guaranteed greater connectivity than is provided by a single concentrator-to-backbone link. To compensate for this we calculated the additional cost of dual homing the concentrators - although no attempt was made to reoptimize the network on the basis of dual homing considerations. Thus the dual homing cost is somewhat of an overestimate of the actual added cost. Dual homing provides a dedicated backup connection to an alternate backbone switch, but this backup is presumed to be idle (except for periodic testing, etc.) during normal operation. In fact, it is the inability of the concentrator to route simulta-

neously over alternate paths that fundamentally distinguishes it from a backbone switch.

All user sites are considered to be potential concentrator and backbone switch locations. In practice such sites may be restricted, for example, to specially secure facilities or where maintenance personnel can be conveniently colocated. We did not allow new nodes to be introduced because of their advantage as a concentrator or switch site. Given the geographical dispersion of the existing sites, this would not lead to a significant improvement.

In our satellite studies we permitted satellite access only in the backbone portion of the network. The satellites are assumed to operate in the multiple access uplink, broadcast downlink mode. With our particular nominal cost assumptions about earth stations, they would not be economically justified in the local access area. In designs where a backbone node has terrestrial connections as well as satellite connections we assumed that a regular packet switch is required in addition to the earth station. In cases where the backbone node has only satellite connections to the other backbone nodes, we assumed the presence of a device - priced at the largest concentrator cost - to handle the local access lines and interface with the earth station.

A typical network topology is shown in Figure 1.

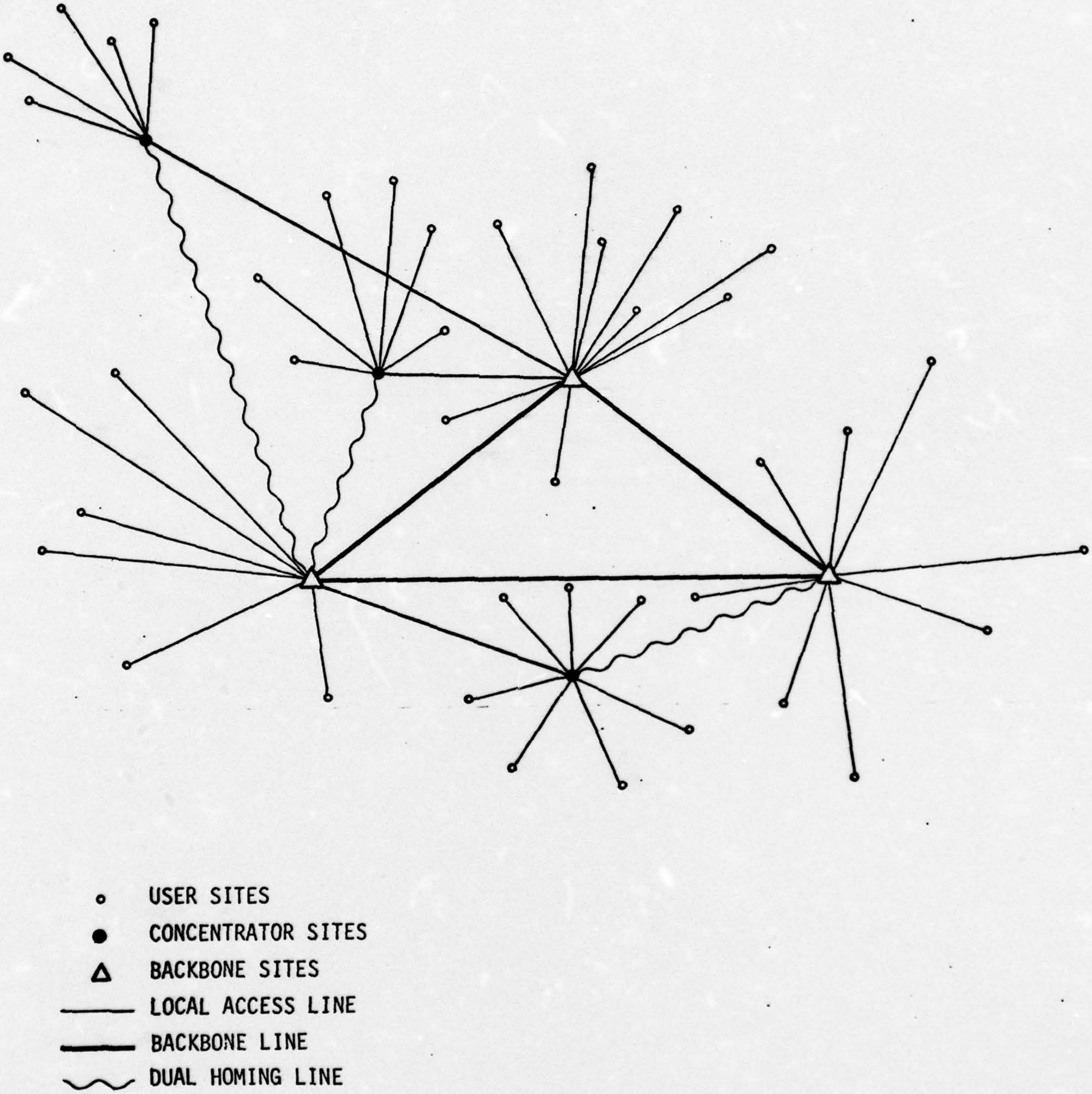

FIGURE 1: TYPICAL TOPOLOGY

6.3 PARAMETERS AND COST MODELS

All cost parameters are either expressed on a monthly basis or on a capital cost basis. Capital costs are assumed to be reduced to an equivalent monthly figure by multiplying by 0.0438 - a factor used in previous NAC studies [NAC, 1975] which includes operation, maintenance and amortization.

6.3.1 Location and Traffic Data

The data base used for the design studies started with a purported AUTODIN II projected 1980 requirement. Requirements to and from points outside the U.S. were discarded. Points within the U.S. whose requirements and/or location were unavailable (because of secrecy) or were otherwise unclear were also deleted. These adjustments left us with a data base with 272 points whose distribution is still very representative of CONUS AUTODIN II and hence of military data transmission requirements in the U.S. in general.

The sums of the input and output requirements had a slight discrepancy (less than 1%) and the input requirements for all points were scaled upward slightly to achieve a precise balance. Since the objective of the study is to expose major trends, and not to do a detailed design for implementation, there was no need to refine or investigate the data base further. The exact total data throughput requirement came out to be 1.833 MBS.

6.3.2 Line Parameters

Real world leased line costs are complex in detail and have strange dependencies such as the types of service (e.g., DDS) currently available and the intricacies of access arrangements. Many of these matters continue to be volatile. We adopted an approach of using the simplest general cost structure that would

be likely to reflect accurately the gross line costs at any time in the foreseeable future.

We assumed a simple tariff model that only has two parameters, a fixed line charge, F_L, independent of distance and a unit mileage charge, L_L. The F_L charge can be assumed to include all termination charges (including modems, local loops, etc.). We further assumed that the line charges vary with the square root of the bandwidth, B (also called line speed in digital transmission). This yields an approximately 40% increase in line cost for a doubling of bandwidth. This latter assumption tracks very well with actual costs at low and intermediate bandwidths but underestimates line costs at higher bandwidths, as represented in Figure 2. This situation probably prevails because of the current small demand for very high (1.544 MBS) bandwidth lines; but physical economies of scale dictate that the square root relationship will be at least approximately true in the long run. Our formula for line cost is thus:

$$\text{Line Cost} = (F_L + L_L \times \text{mileage})\sqrt{B}.$$

We have thus removed all of the idiosyncrasies of existing tariffs. To make the problem somewhat more realistic we retained the complexity of having only a small set of line speed choices reflective of the current options, with the consequent large jumps between options. Although large jump discrete capacity options greatly increase the complexity of the design effort, having continuous line capacity options available might distort the applicability of the results. The speed options with their respective end costs and mileage charges are given in Table 1. The network designer and design programs could pick multiple lines between two points in the backbone portion of the network where the alternate routing capability reduces the sensitivity of the network to sharp design transitions in line speed. We introduced some artificial line speeds in the local access portion of the network to smooth the otherwise large gaps and give the design process additional stability.

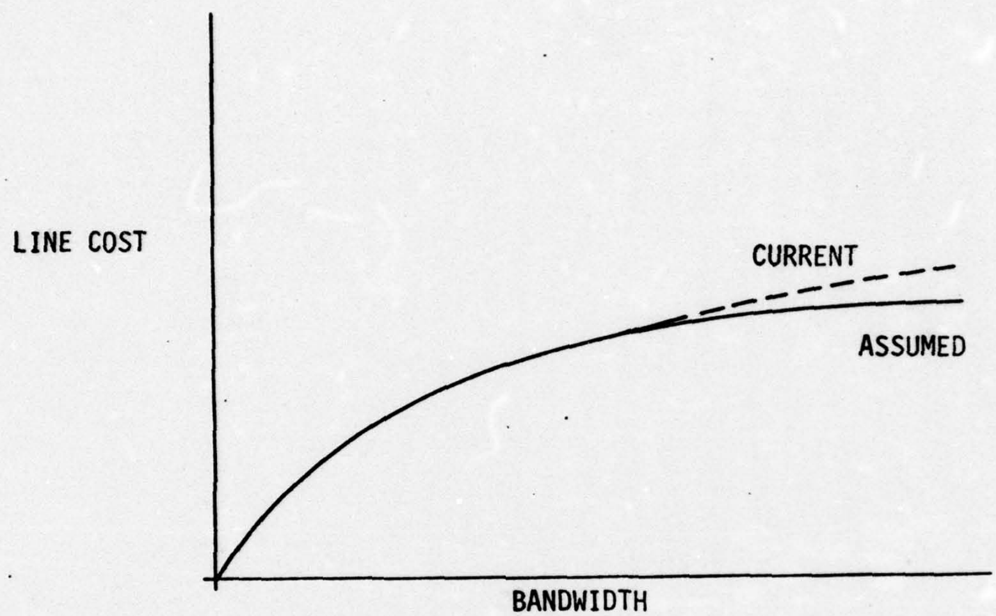

FIGURE 2: SQUARE ROOT RULE FOR LINE COST

SPEED (KBS)	COST/MILE ($/MO.)	COST/END ($/MO.)
1.2	.30	64
2.4	.42	90
4.8	.60	125
9.6	.84	175
19.2	1.20	250
50	1.92	400
100*	2.69	560
230	4.22	880
460*	5.97	1244
1544	10.97	2288

*Local access options only.

TABLE 1: LINE SPEED OPTIONS

6.3.3 Backbone Operation

Since the design methodology adopted (discussed in detail in Section 6.4.1) did not have a fixed backbone delay requirement, there was very little sensitivity to the specific operational parameters selected. For example, the nodal processing time per packet was assumed to be a constant 1 ms., and would influence only the actual delay, but have absolutely no influence on the relative design results. A 7% fraction of the backbone line capacity was assumed to be devoted to activities, such as routing table updates, status monitoring, etc., which are network overhead operations that do not depend directly on traffic volume.

The issue of the appropriate packet protocol overhead factor, p_o, is somewhat more complex. This factor accounts for such items as headers, acknowledgments, and retransmission (due primarily to errors) which are traffic related. With a fixed bit error rate - E, header size - H bits, and acknowledgment size - A bits, p_o is a function only of the packet size distribution. If we approximate by assuming all packets are of the size equal to the average, P, we can easily compute p_o as a function of P.

We make this more explicit with the following first-order model: we assume the only (primary) effect limiting the increase in packet size is the resulting overhead from retransmissions due to E; we assume the only (primary) effect limiting the decrease in packet size is the resulting overhead from headers and hop-by-hop acknowledgments. The latter overhead is simply

$$\frac{H+A}{P}.$$

The probability of a correct bit is 1-E so the probability of at least one error in a packet of size P is

$$1-(1-E)^P.$$

This yields a retransmission overhead of

$$\frac{1}{(1-E)^P} - 1.$$

The total overhead is thus

$$p_o = [\frac{1}{(1-E)^P} - 1] + [\frac{H+A}{P}].$$

Letting $E=10^{-4}$, and H=A=150 bits, we generate the following values:

P(bits)	$[\frac{1}{(1-E)^P} - 1]$	$[\frac{H+A}{P}]$	p_o
500	.05	.60	.65
1000	.11	.30	.41
1500	.16	.20	.36
2000	.22	.15	.37
3000	.35	.10	.45
5000	.65	.06	.71

TABLE 2: PACKET PROTOCOL OVERHEAD

The minimum packet overhead is achieved in the neighborhood of P=1500 bits. Based on these results we set the packet protocol overhead to a nominal value of 35%. Variations in the value of E, H, A and P would impact p_o and primarily affect the backbone design and cost. Design sensitivity to variations in p_o is explored later.

The average packet length need not be assigned a specific nominal value. Different assumptions for the average packet length would affect the absolute delay performance of the networks obtained, and also influence their relative performance if an altered average packet length induces a reassessment of the packet protocol overhead factor and/or the switch costs. The packet protocol overhead factor, p_o, scales the backbone traffic which will impact the required throughput in the backbone network.

More specifically, a change in the packet size would scale the line delays and change p_o if the protocols (headers, ACK's, etc.) remained constant. Under our lack of specific delay criteria, scaling of the line delays causes an equivalent scaling of the end-to-end delays except for the nodal processing delays which remain fixed. The nodal processing delays were only a significant portion of the end-to-end delays at the highest traffic levels studied. A change in p_o shifts the operating point on the throughput vs. delay curves and may cause the accept/reject decision for a design to be reversed.

In any case, the designs reported in the next section were stable for all packet protocol overhead factors in the neighborhood of 35% (say, at least through 40%). In summary, because of our design methodology, the assumption on packet size is significant only as it reflects the proper range of overhead. The protocol overhead factor selectively scales the backbone traffic, may influence the switch throughput cost computation, but will not affect the local access line traffic calculations.

6.3.4 Switch Parameters

A simplified model was adopted for the cost dependencies of the packet switches. We assumed the cost consisted of a fixed cost component and a variable cost component having linear dependence on switch throughput. Switch throughput consists of two components: the local traffic that has both its origination and destination at points homed to the same backbone switch, and which therefore does not transit the backbone links; and traffic that passes through at least one backbone link and thus contributes to the throughput at more than one switch.

The switch processing capability is related both to packet throughput and bit throughput. If K_1 is an assumed switch capital cost per bit of throughput capability, K_2 is an assumed switch

capital cost per packet of throughput capability, and F_s is a fixed cost per switch, we have

$$\text{Switch cost} = F_s + (K_1(1+p_o) + \frac{K_2}{P})\, T$$

where T is the sum of the local traffic and backbone traffic in bits per second without overhead. We have increased the local bit traffic component by the overhead factor also to account for polling (if any), header, framing, acknowledgments, retransmissions, and other facets of local access protocols not reflected in the basic site I/O requirements data. P and p_o are not independent and are themselves functions of other parameters as shown in the last subsection. We can simplify this cost equation by lumping all the parameters in the coefficient of T into a single linear switch throughput cost factor, L_S, and add a scale factor, S, nominally set equal to one, that permits networks to be appraised at different line cost-to-switch cost ratios.

Our simplified cost calculation for switches is thus

$$\text{Switch Cost} = S(F_S+L_ST).$$

The nominal values used in this study are F_S=\$100,000 and L_S=\$.1/BPS so that a switch with one MBS throughput has a cost of \$200,000. Values of S less than one were applied to these costs.

Note that with this simple switch cost relationship we can lump all the switches together; multiply the number of switches by F_S and add the total throughput (local plus backbone at each switch) multiplied by the L_S factor to get the unscaled switch cost. Thus given only two parameters, the number of backbone switches, N_S, and the sum of the T's for the switches, we can price out the switch costs of a given network under a variety of switch cost assumptions. Additional complexity - not considered in this report - would be introduced by pricing switches in different size ranges with different

parameters, ultimately going to discrete pricing. This would make repricing a network under different technology assumptions a chore.

An important point to note is that, when the number of backbone sites is increased, in general, we have a correlated increase in backbone throughput. A smaller portion of the traffic is likely to be local to a switch and the average number of backbone hops traversed between sources and destinations increases since the average node degree does not increase proportionately. We note again that T is calculated independently of packet overhead so there is no additional cost penalty due to overhead when traffic switches from local to backbone traversing as additional backbone nodes are introduced.

6.3.5 Concentrator Parameters

We assumed the existence the three generic concentrator models designed to handle low (voice grade or below), wideband, and extra wideband requirements as presented in Table 3 below.

Throughput Capacity (KBS)	Nominal Cost ($)
9.6	10,000
50	50,000
230	100,000

TABLE 3: CONCENTRATORS

The hardware cost scale factor, S, was applied to the concentrator costs as well as the switch costs, so the table above represents the highest costs used in the study. No restrictions were placed on the number of ports available at a particular concentrator.

6.3.6 Local Access Utilization

Sites engaged exclusively in batch or large file transfer operations can get very high utilization of their local access lines without performance degradation. For interactive users, the utilization has a significant impact on delay performance. Since we did not have a characterization of the traffic type composition for the individual sites, and to retain the formulation simplicity, we adopted a uniform rule of limiting the steady state traffic on any access line to 65% of its capacity. This assures good performance stability even for highly random interactive traffic. The choice of values other than 65% would be roughly equivalent to scaling local access costs relative to other costs in its impact on the design. As pointed out before, individual users could selectively upgrade or degrade their access lines with no significant effect on the rest of the network.

6.3.7 Satellite

For designs using a satellite we assumed multiple access uplinks and broadcast mode downlinks. Each earth station was assumed to nominally cost $1,000,000 (equivalent to $43,800/month for operation, maintenance and amortization). The satellite bandwidth was assumed to be allocated in units of 1.544 MBS - we are only concerned here with the high throughput range. We again assumed a square root increase of cost versus capacity, with a nominal cost of $30,000/month for a single 1.544 MBS channel. The cost is assumed to absorb any proportional additional bandwidth needed to support a satellite protocol. Thus for a throughput, T, through the satellite the nominal cost is

$$\text{Nominal Satellite Channel Cost} = 3\text{x}10^4\sqrt{N}$$

where N is the smallest integer satisfying $N \geq T/1.544$ MBS.

For a single channel this cost is equivalent to a 2290 mile terrestrial channel of the same bandwidth. Scale factors less than one were subsequently applied to the satellite channel costs.

6.4 DESIGNS

6.4.1 Methodology

6.4.1.1 Backbone Assignments and Traffic Matrix

Since we did not have a source-destination traffic matrix for the 272 sites involved in our study, we adopted the following technique to obtain a backbone traffic matrix.

1. A set of backbone node locations is determined by a combination of automatic and interactive techniques.

2. Local sites are assigned to the backbone nodes on some automatic and/or interactive basis. Usually the rule used was to assign a site to the closest backbone node.

3. The total transmitted traffic and total received traffic from a backbone node to its assigned local sites was calculated from the local site I/O requirements data.

4. The total transmitted traffic for each backbone node was assigned to be received by the other backbone nodes and itself in the proportion to which each node's total received traffic was a fraction of the entire network's received traffic. Thus, for example, a backbone node whose assigned local sites receive 25% of the total received traffic from all network sites, would be assumed to receive its share

of 25% of the traffic transmitted by every other node. Also 25% of its own transmitted traffic is assumed not to require transiting the backbone links; this is traffic local to the switch. In other words, sources distribute their traffic to destinations in direct proportion to the magnitude of each destination's relative receive requirements. (See Figure 3).

The above method is a reasonable assumption in the face of lack of specific data. It is also well established that the backbone design is very sensitive to overall traffic levels, but not, in general, sensitive to the specific traffic distribution.

Note that with the same site traffic levels, the backbone throughput will depend somewhat on the local site-to-backbone node connections and, in particular, will be affected by the number of backbone nodes selected.

6.4.1.2 Design Acceptance

Since one of our objectives is to study design variations as the traffic level is varied over a wide range, it was not possible to compare networks on the basis of equivalent backbone delays. The backbone link capacities are determined largely by throughput requirements, and this could vary considerably even at the same overall traffic level as the number of backbone nodes in the design changes.

Consequently, for each traffic scale factor, hardware scale factor, and transmission media selection, we sought to find the best (cheapest) obtainable acceptable network by rejecting networks that could not satisfy the throughput requirements at a stable point on their throughput versus delay curves. Although "stability" in the sense used here is somewhat subjective, it offered no significant

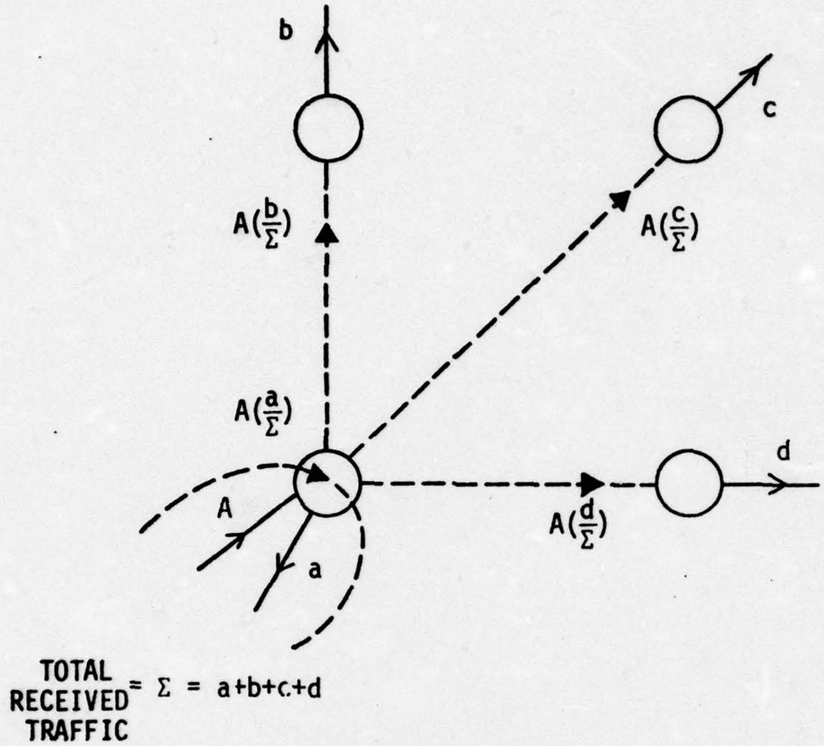

FIGURE 3: SCHEMATIC OF BACKBONE TRAFFIC DISTRIBUTION ASSUMPTION

obstacles in practice. Since the possible line capacities are chosen from a small discrete set, well designed networks will often shift radically from clearly acceptable to clearly unacceptable if, among the discrete choices available, smaller (and less costly) capacities are substituted.

The designs obtained as "best" are usually surrounded by similar costing designs, often with quite different topologies, and thus, in a sense, are representatives of a whole class of good designs. The designs reported are not strictly guaranteed to be optimal, but represent the best that can be obtained under current technology with reasonable effort.

The selection of a single "best" design for one design variable point may have involved the generation of literally hundreds of alternate designs.

6.4.1.3 Study Variables

The basic study variables were explored as described below:

1. Traffic level - Sets of designs were obtained for three traffic levels: 1.83 MBS (nominal), 18.3 MBS (10 times nominal), 1.83 MBS (100 times nominal).

2. Cost scale factor, S - Four different ratios of hardware cost to line cost were explored for each traffic level: S=1 (nominal), S=1/2, S=1/5, S=1/10.

3. Number of backbone switches - The most important decision alternative and design variable under the architecture adopted is the number of backbone switch sites. For each traffic level and

cost scale factor, best designs were obtained for the range of two to eight backbone sites. Where trends were not already obvious, the range was extended to designs with 12 and 25 backbone switch locations.

4. Dual homing - The added cost of dual homing concentrators to an alternate backbone switch - without redesign - were determined for the lowest traffic level (full range of cost ratios and number of backbone nodes). Concentrators were not significant in the designs at other traffic levels and thus neither would be the dual homing costs.

5. Satellite usage - The satellite studies were confined to the 18 MBS traffic level case and the trends exposed should be reflective of what would occur at the other traffic levels. Designs were generated for the range of number of backbone nodes for the case of only satellite links in the backbone network; each backbone site is assumed equipped with an earth station for satellite access. Progressively lower satellite channel costs and earth station costs were applied to the designs obtained. Then for a representative fixed number of backbone nodes, designs were obtained for various numbers of earth stations under two different assumptions:

   a. Satellite connectivity; backbone sites without earth stations home to nearest earth station.

b. Mixed satellite and terrestrial connectivity; guaranteed minimum 50 KBS two-connected terrestrial "thin-line" path between any pair of backbone nodes.

6. Packet protocol overhead - Changes in protocols, packet size, or both will effect the packet protocol overhead. The primary design effect will be altered capacities and/or topology in the backbone links. Switch costs will also be effected and may shift the optimum number of switches. There will be no affect on the local access design. Switch locations will be affected for large swings in overhead since this selectively scales the backbone line costs.

   We studied the effect of a wide range of overheads on the backbone network needed to support the traffic from a fixed set of 5 switch locations for each of the three traffic levels.

6.4.2 Results

The results below are given both tabularly and graphically. They were obtained using the parameters stated in Section 6.3 with the methodology given in Section 6.4.1. The latest version of NAC's interactive design software was used throughout as the main design tool, supplemented by human designer judgment.

Most of the designs obtained - particularly the backbone node locations - would vary little and insignificantly under a variety of alternate parameter assumptions. Enough information is

presented in tabular results below to "unpack" the design properties and vary the assumptions. Thus, for example, knowing the number of backbone sites and total backbone switch cost, one could calculate the total throughput, T, and then cost out the switches under different assumptions. Different switch costs would have a big effect on the optimal number of switches but would not have much impact on optimal location of a given number of switches. The best locations are primarily determined by a tradeoff of backbone line cost and local access cost - the former carrying traffic more directly, the latter carrying traffic less directly but in higher bandwidth lines.

6.4.2.1 Terrestrial Designs

Figures 4-15 and Tables 4-15 present the basic terrestrial design costs for the different traffic levels and hardware cost scale factors as the number of backbone nodes is varied.

Figures and Tables 16-19 show the effect of added dual homing costs to the networks of nominal traffic level and hardware cost (Figures and Tables 4-7). Note that as the number of backbone nodes increase the dual homing costs quickly die off. This occurs because the cost justification for local access concentrators disappears as more backbone nodes are distributed and also because the cost of the dual homed line gets smaller as closer alternate backbone sites become available. At higher traffic levels this effect was even more pronounced with dual homing costs virtually disappearing when 3 or more backbone switches became available for the case of 10 times nominal traffic.

6.4.2.2 Satellite Designs

Table 20 shows the results of replacing the backbone portion of the networks that carried 10 times the nominal traffic with satellite links. The number of 1.544 MBS satellite channels needed to support the packet throughput (with the allowance for

satellite protocol overhead reflected through the cost factor) is shown explicitly. Each $1,000,000 ground station is assumed to require a $100,000 local access-to-ground station interface device. Local access costs otherwise remain exactly as they were for the nominal hardware cost terrestrial case. Small cost reductions (1%) might be achievable in the local access area by relocating the backbone nodes. These were located for best overall cost in the terrestrial design where some consideration - though small - had to be given to the distance dependent terrestrial backbone line cost. To obtain this small perturbation would have involved an expensive reoptimization of all the local access designs and hence was not done. Taking the backbone locations (and hence the local access costs) to be fixed, the backbone portion can be recosted for any alternate satellite assumptions using the parameters N and the number of backbone sites. The costs in Table 20 have been computed using the nominal parameters of Section 6.3.7 and are plotted on Figure 20. The results for the same case with terrestrial backbone links is plotted for convenient comparison. Tables and Figures 21-23 show the effect of progressively reducing the satellite channel cost on the designs with only satellite backbone connections. Fixing the satellite channel cost at 1/2 nominal, Tables and Figures 24-26 show the effect of reducing the hardware cost, now including the ground station and interface cost, on the backbone and total network cost.

For our next study, we froze the backbone node positions of the 5 switch network for the case of traffic 10 times nominal and nominal hardware cost. We then proceeded to optimally select different size subsets of the 5 nodes to have ground stations. The remaining backbone nodes, if any, were homed to the nearest ground station. Thus network interface devices (costed at largest concentrator cost) were required at each backbone node. The results are tabulated in Table 27a. Note that no switch costs are involved and that the total costs refer to backbone costs

only. The 5 ground station case corresponds to the 5 backbone node design in Table 20 (only satellite links in backbone network) and the 0 ground station case in Tables 27a and 27b corresponds to the 5 backbone node pure terrestrial link case of Table 8. The costs for these two extreme cases also appear in Figure 20 as the backbone network costs (lower two curves) at the 5 backbone node level.

For comparison we also designed networks for the same situation but with an additional requirement of maintaining at least 50 KBS two-connected terrestrial path connectivity (for backup, high priority, or low delay traffic) between all five backbone nodes. This, of course, now required switches at these backbone sites. The results are tabulated in Table 27b. The backbone cost results of Tables 27a and 27b are plotted for comparison in Figure 27.

We next sought to investigate the sensitivity of our designs and results to some critical network model assumptions and parameters. In Tables and Figures 28 through 31 we show the effect of providing an additional line option, 6.176 MBS (4 x 1.544 MBS), in the 100 times nominal traffic case across all hardware cost scale factors. Tables and Figures 32-34 show the effect of varying the packet protocol overhead, p_o, on the backbone line cost for the networks with 5 backbone nodes at the various traffic levels.

Traffic-nominal Hardware Cost-nominal

# of BB	BB Line Cost	Switch Cost	L.A. Cost	Total Cost
2	13	21	241	275
3	40	27	199	266
4	40	32	188	259
5	43	37	175	255
6	51	44	168	263
7	56	50	161	267
8	64	55	153	272

TABLE: 4

Traffic-nominal Hardware Cost-1/2

# of BB	BB Line Cost	Switch Cost	L.A. Cost	Total Cost
2	13	10	236	260
3	40	13	197	251
4	40	16	188	243
5	43	18	173	235
6	51	22	167	240
7	56	25	160	241
8	64	27	153	244

TABLE: 5

Traffic-nominal Hardware Cost -1/5

# of BB	BB Line Cost	Switch Cost	L.A. Cost	Total Cost
2	13	4	206	223
3	40	5	185	231
4	40	6	182	228
5	43	7	169	220
6	51	9	167	226
7	56	10	160	225
8	64	11	153	228

TABLE: 6

Traffic-nominal Hardware Cost-1/10

# of BB	BB Line Cost	Switch Cost	L.A. Cost	Total Cost
2	13	2	202	217
3	4	3	182	225
4	40	3	176	219
5	43	4	166	213
6	51	4	166	221
7	56	5	161	221
8	64	5	153	222

TABLE: 7

Note: Costs for all tables expressed in thousands of dollars.

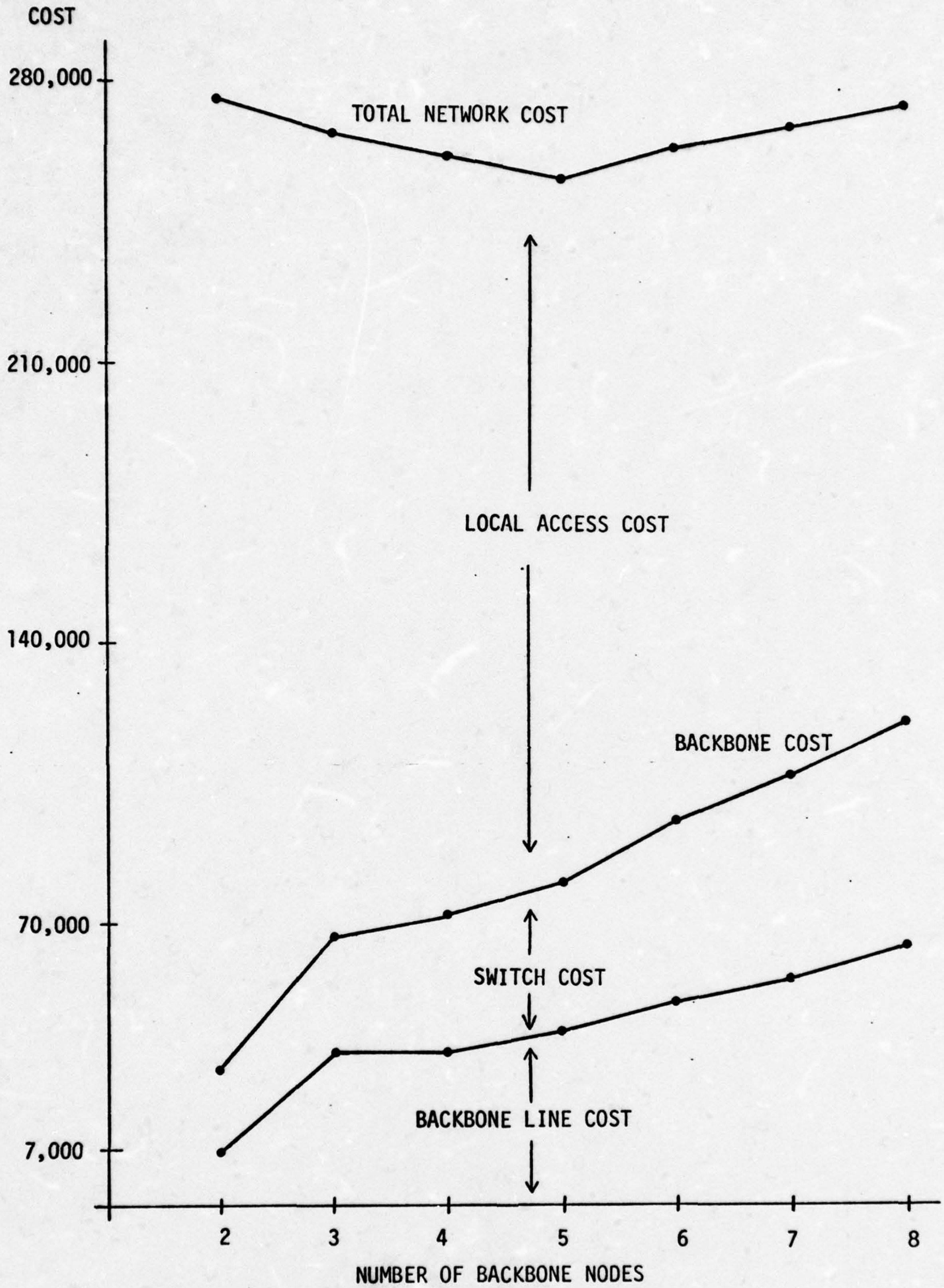

FIGURE 4: TRAFFIC - NOMINAL
HARDWARE COST - NOMINAL

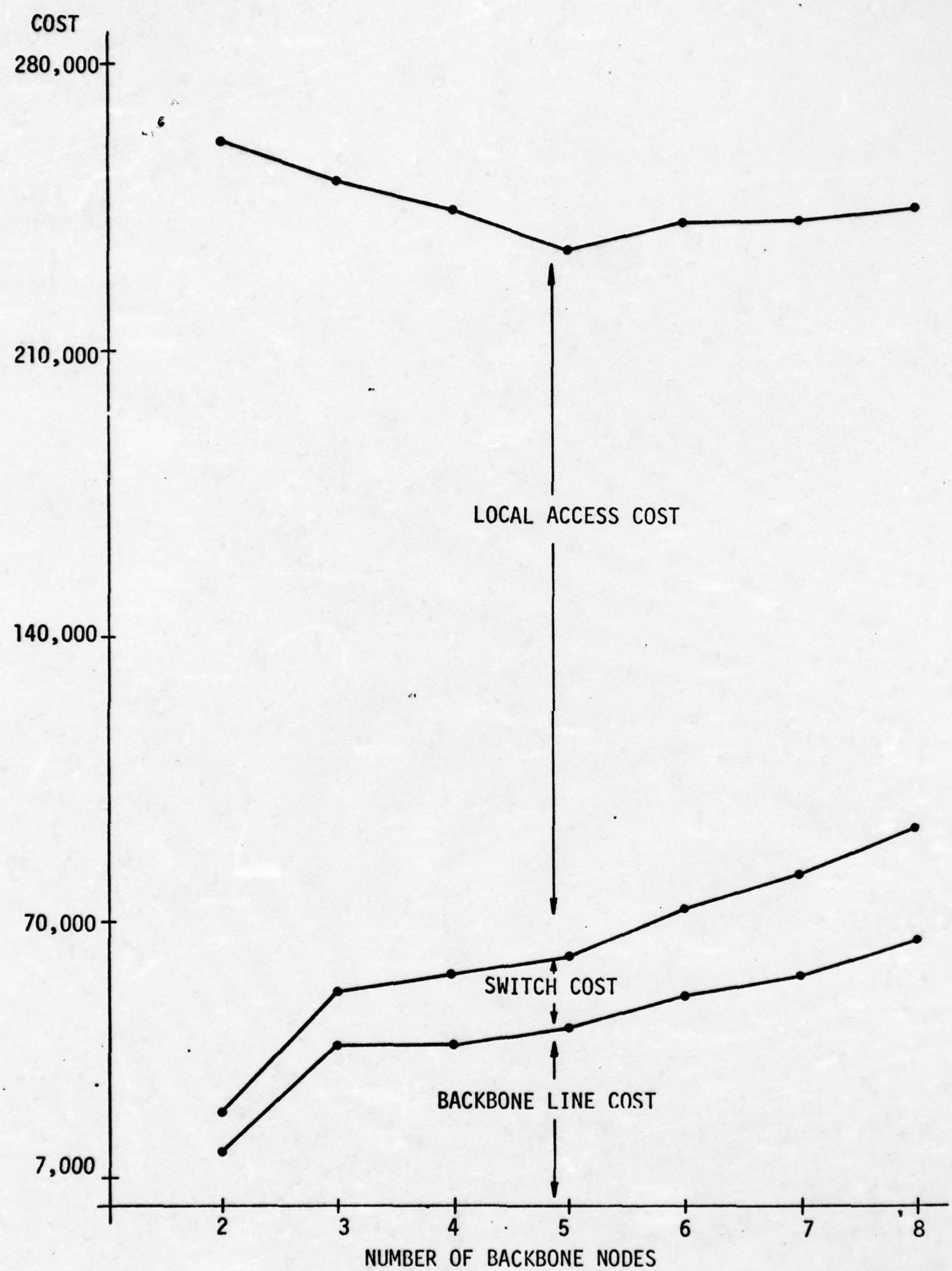

FIGURE 5: TRAFFIC - NOMINAL
HARDWARE COST - 1/2

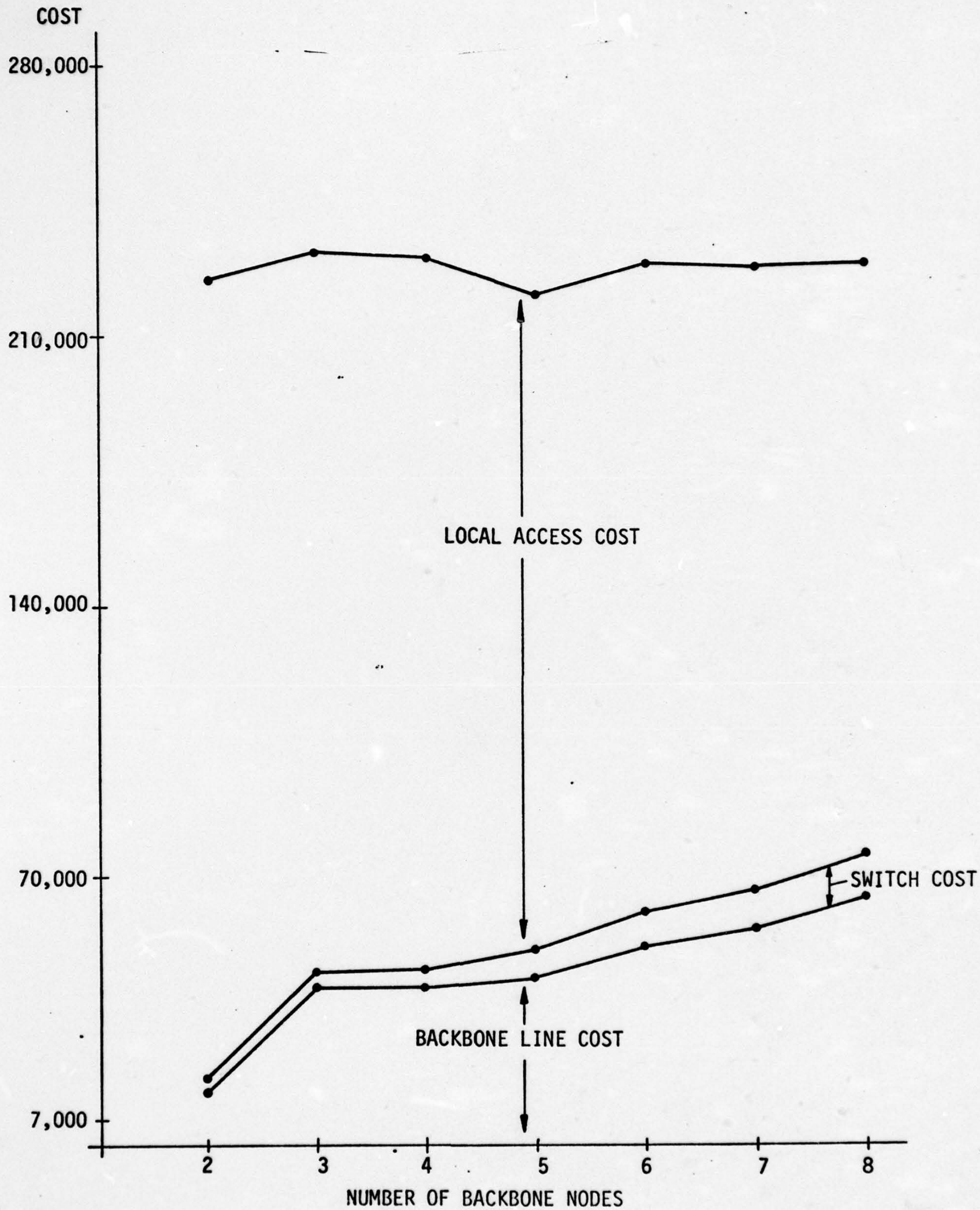

FIGURE 6: TRAFFIC - NOMINAL
HARDWARE COST - 1/5

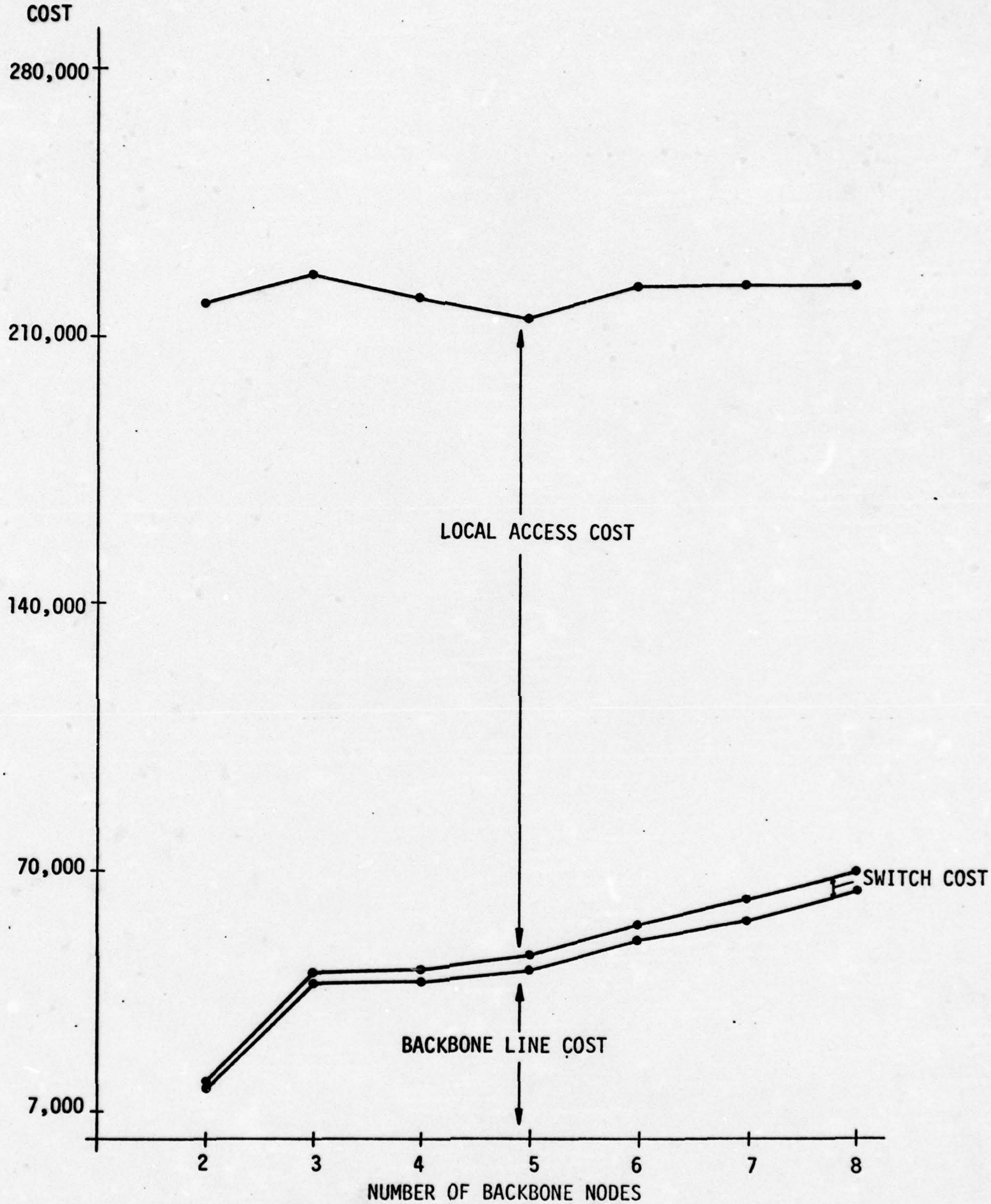

FIGURE 7: TRAFFIC - NOMINAL
HARDWARE COST - 1/10

Traffic-10 times Hardware Cost-nominal

# of BB	BB Line Cost	Switch Cost	L.A. Cost	Total Cost
2	66	127	808	1001
3	140	145	613	897
4	150	160	576	886
5	167	177	537	883
6	190	207	517	913
7	208	223	498	928
8	214	228	475	917
12	265	300	426	991
25	377	463	337	1176

TABLE:8

Traffic-10 times Hardware Cost-1/2

# of BB	BB Line Cost	Switch Cost	L.A. Cost	Total Cost
2	66	64	808	938
3	140	72	613	825
4	150	80	576	806
5	167	90	537	793
6	190	103	519	810
7	208	112	498	817
8	214	114	475	803
12	265	150	426	841
25	377	231	337	945

TABLE:9

Traffic - 10 times Hardware Cost-1/5

# of BB	BB Line Cost	Switch Cost	L.A. Cost	Total Cost
2	66	25	808	900
3	140	29	608	776
4	150	32	576	758
5	167	36	537	739
6	190	41	517	747
7	208	45	598	750
8	214	46	475	735
12	265	60	426	751
25	377	93	337	806

TABLE:10

Traffic-10 times Hardware Cost-1/10

# of BB	BB Line Cost	Switch Cost	L.A. Cost	Total Cost
2	66	13	808	887
3	140	14	605	760
4	170	16	576	741
5	167	18	537	721
6	190	21	517	727
7	208	22	498	728
8	214	23	475	712
12	265	30	426	721
25	377	46	337	760

TABLE:11

Note: Costs for all tables expressed in thousands of dollars.

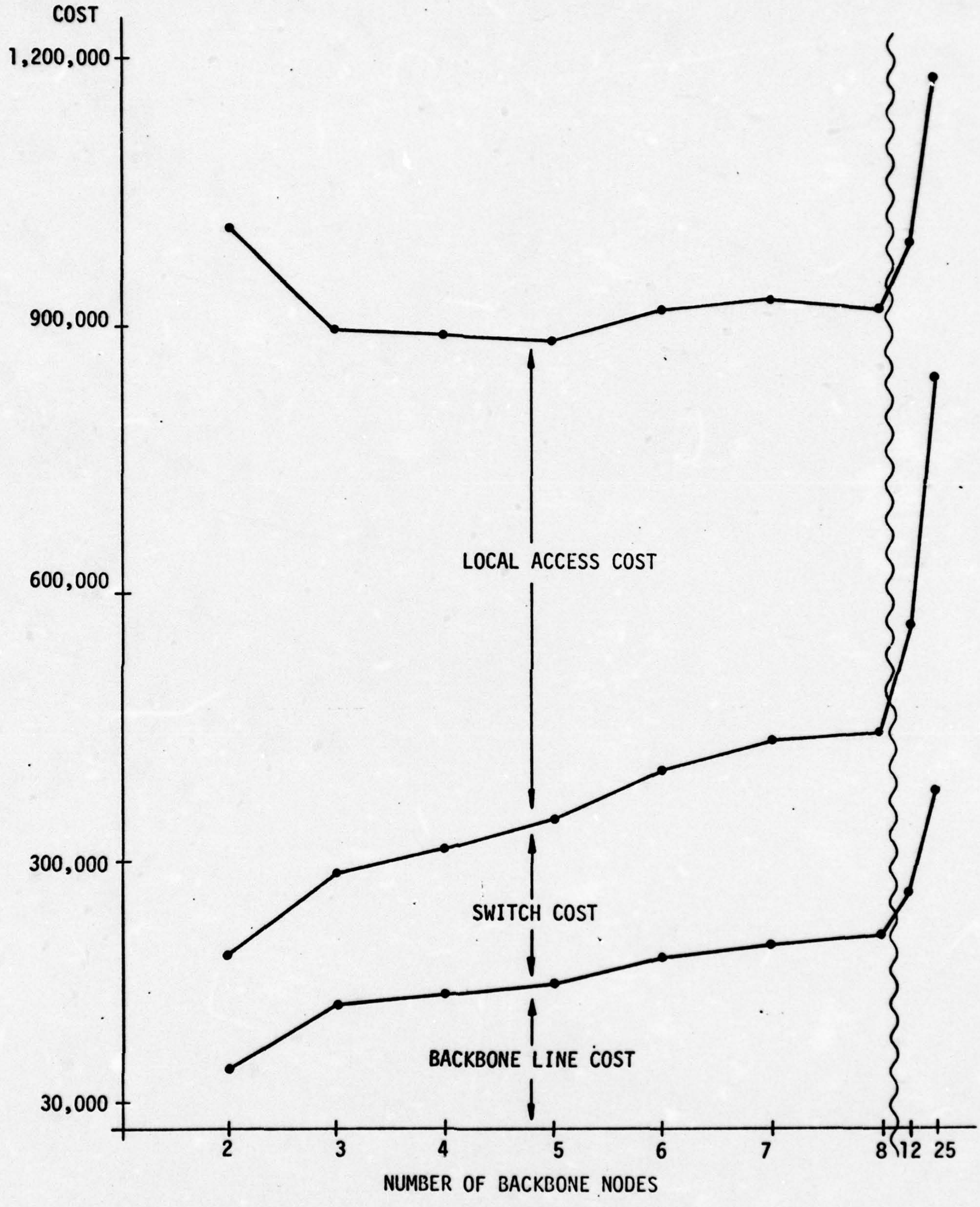

FIGURE 8: TRAFFIC - 10 TIMES
HARDWARE COST - NOMINAL

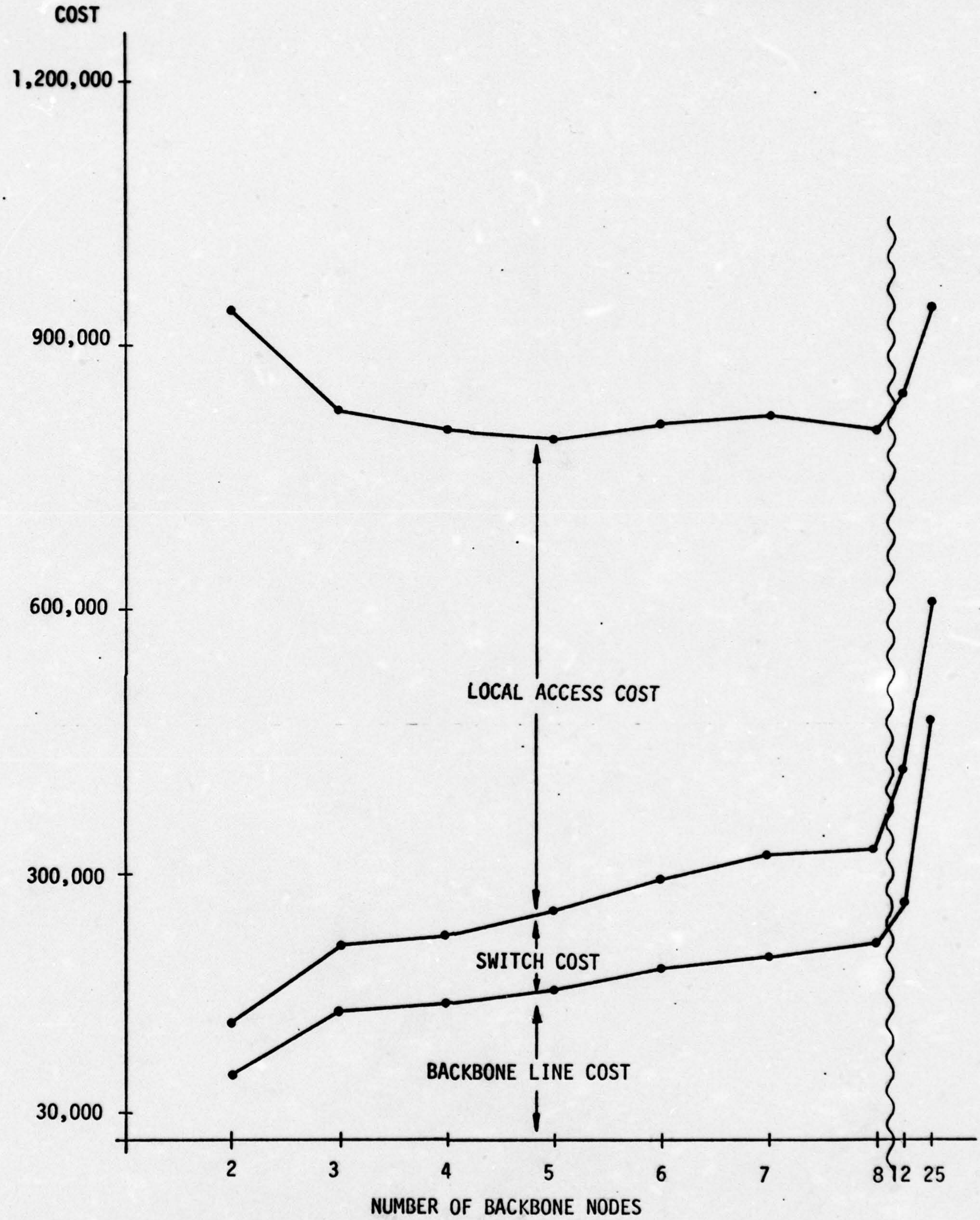

FIGURE 9: TRAFFIC - 10 TIMES
HARDWARE COST - 1/2

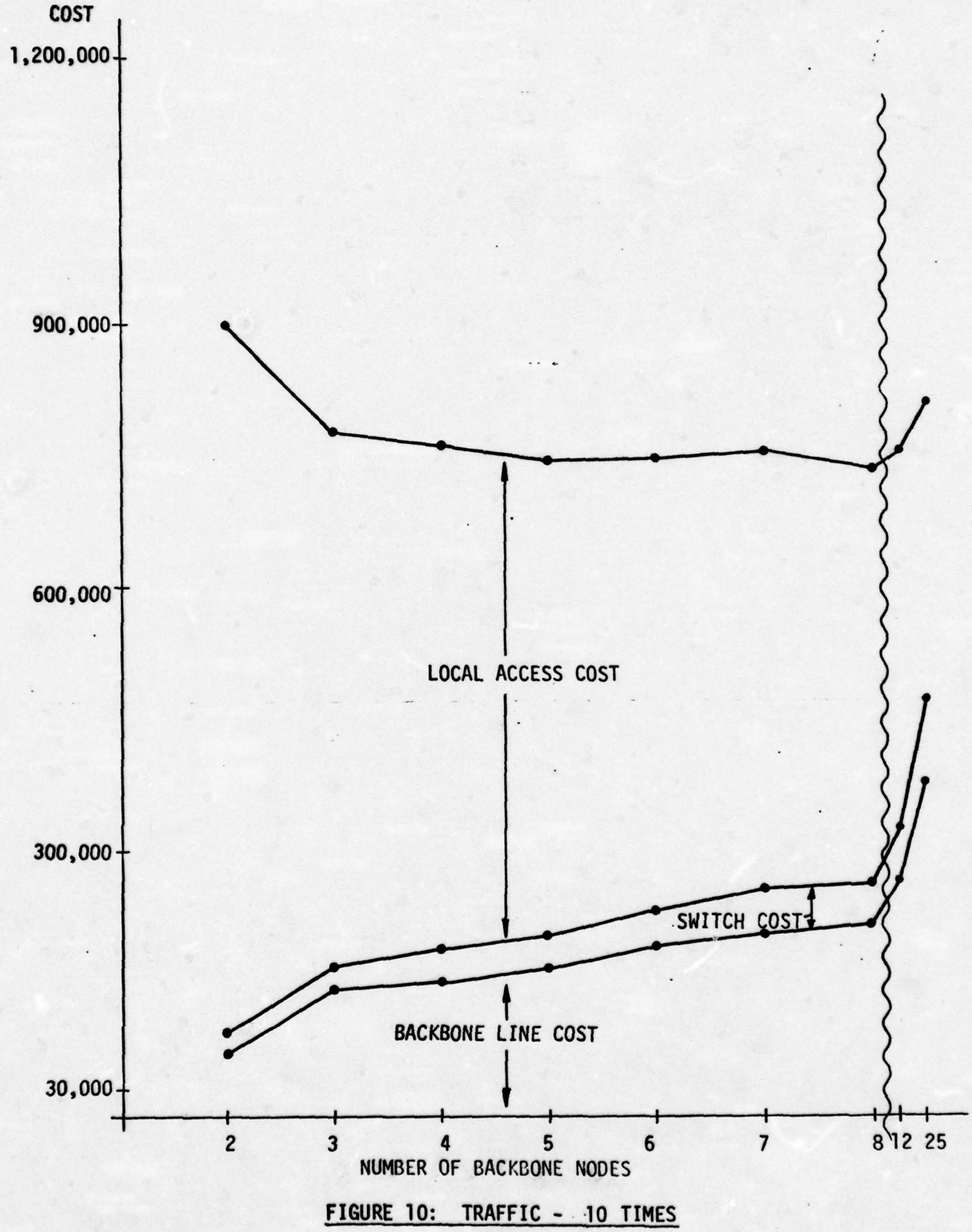

FIGURE 10: TRAFFIC - 10 TIMES

HARDWARE COST - 1/5

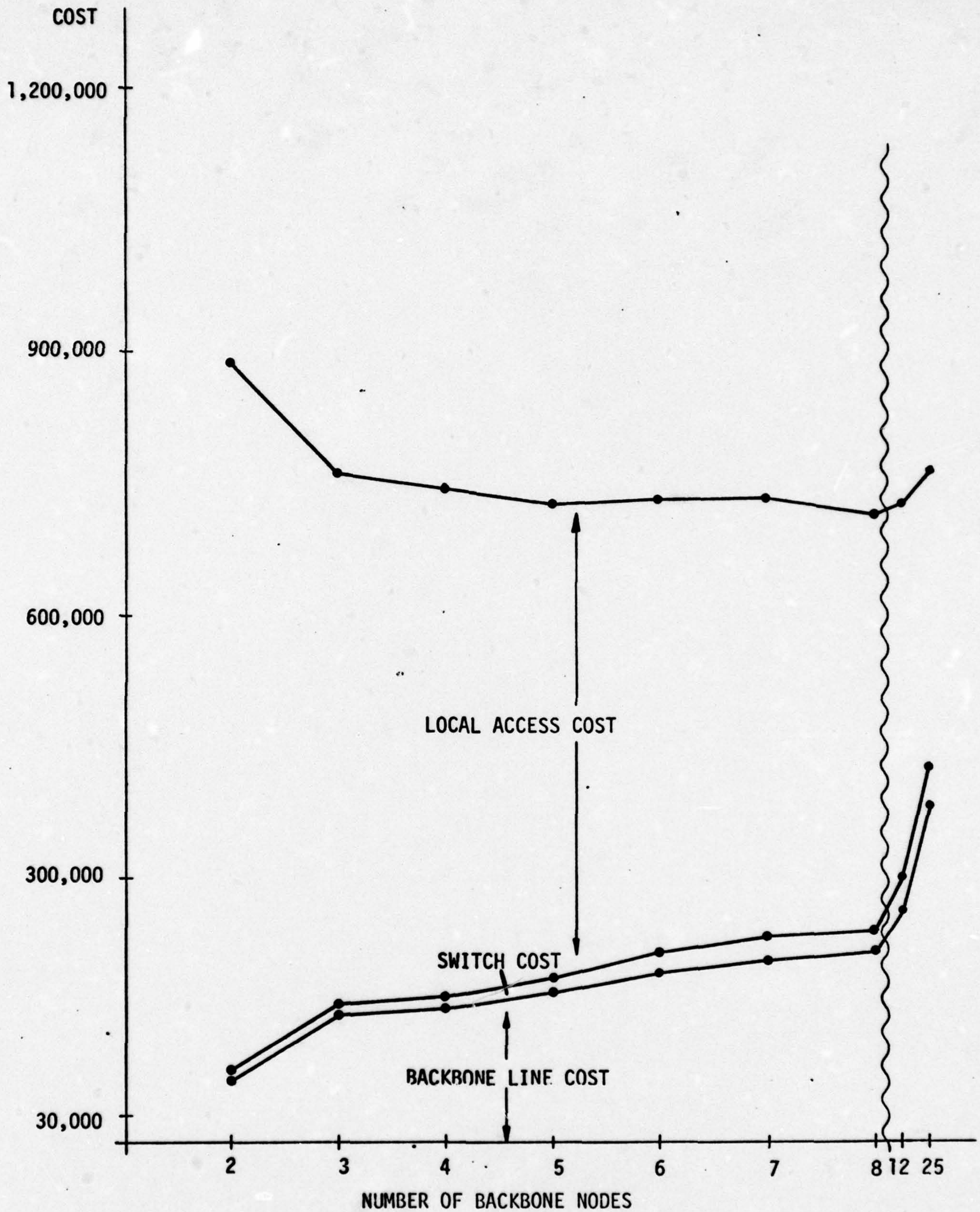

FIGURE 11: TRAFFIC - 10 TIMES
HARDWARE COST - 1/10

Traffic-100 times   Hardware Cost-nominal

# of BB	BB Line Cost	Switch Cost	L.A. Cost	Total Cost
2	646	1205	3620	5482
3	1420	1335	2790	5544
4	1547	1464	2588	5599
5	1579	1515	2349	5443
6	1949	1810	2272	6031
7	2121	1915	2131	6167
8	2241	1947	2040	6228

TABLE:12

Traffic-100 times   Hardware Cost-1/2

# of BB	BB Line Cost	Switch Cost	L.A. Cost	Total Cost
2	646	602	3620	4869
3	1420	668	2790	4877
4	1547	732	2588	4867
5	1579	757	2349	4686
6	1949	905	2272	5125
7	2121	958	2131	5210
8	2241	974	2040	5255

TABLE:13

Traffic-100 times   Hardware Cost-1/5

# of BB	BB Line Cost	Switch Cost	L.A. Cost	Total Cost
2	646	241	3620	4507
3	1420	267	2790	4476
4	1547	293	2588	4428
5	1579	303	2349	4231
6	1949	362	2272	4582
7	2121	383	2131	4635
8	2241	389	2040	4670

TABLE: 14

Traffic-100 times   Hardware Cost-1/10

# of BB	BB Line Cost	Switch Cost	L.A. Cost	Total Cost
2	646	120	3620	4387
3	1420	134	2790	4343
4	1547	146	2588	4281
5	1579	152	2349	4080
6	1949	181	2272	4401
7	2121	192	2131	4444
8	2241	195	2040	4476

TABLE: 15

Note: Costs for all tables expressed in thousands of dollars.

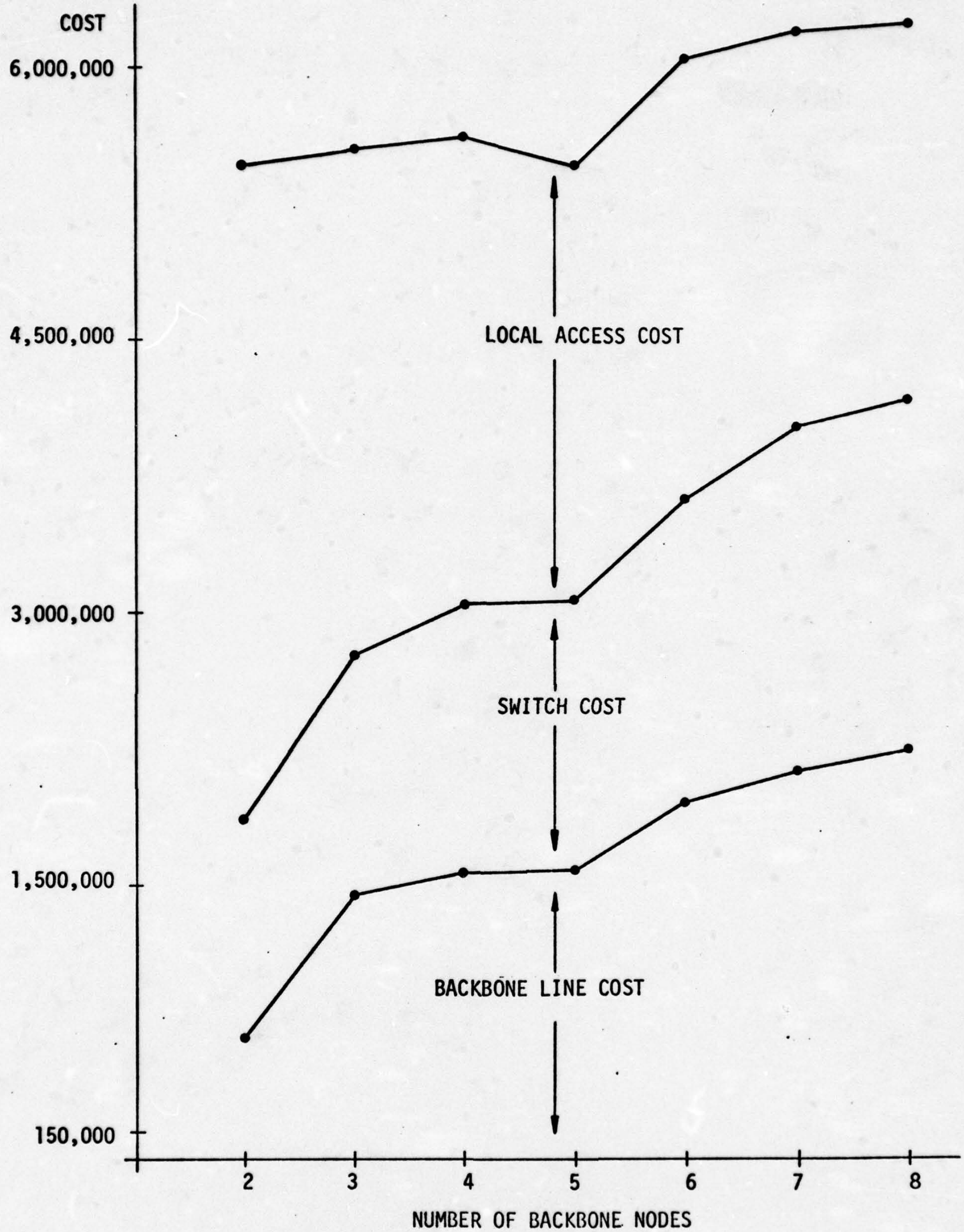

FIGURE 12: TRAFFIC - 100 TIMES
HARDWARE COST - NOMINAL

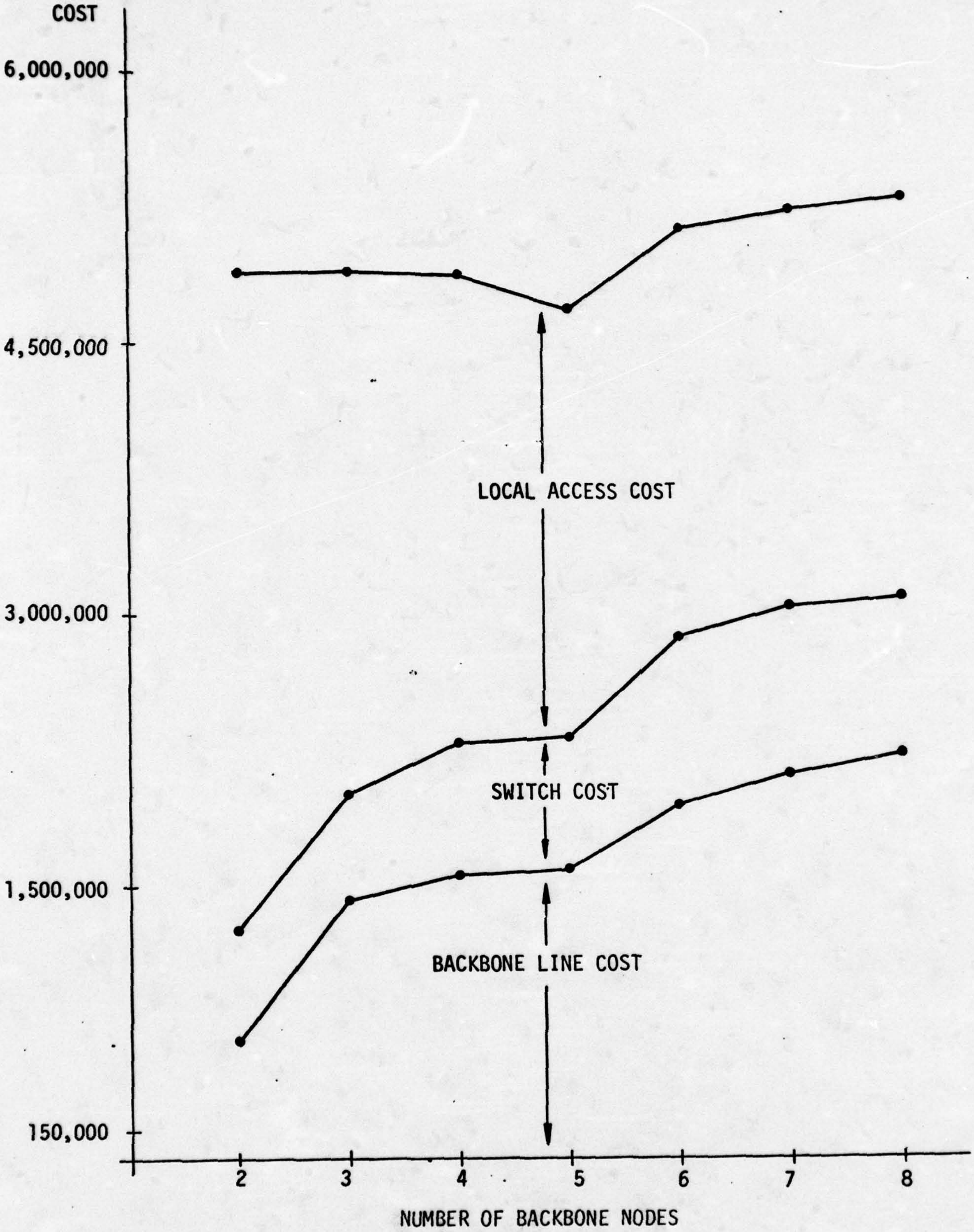

FIGURE 13: TRAFFIC - 100 TIMES
HARDWARE COST - 1/2

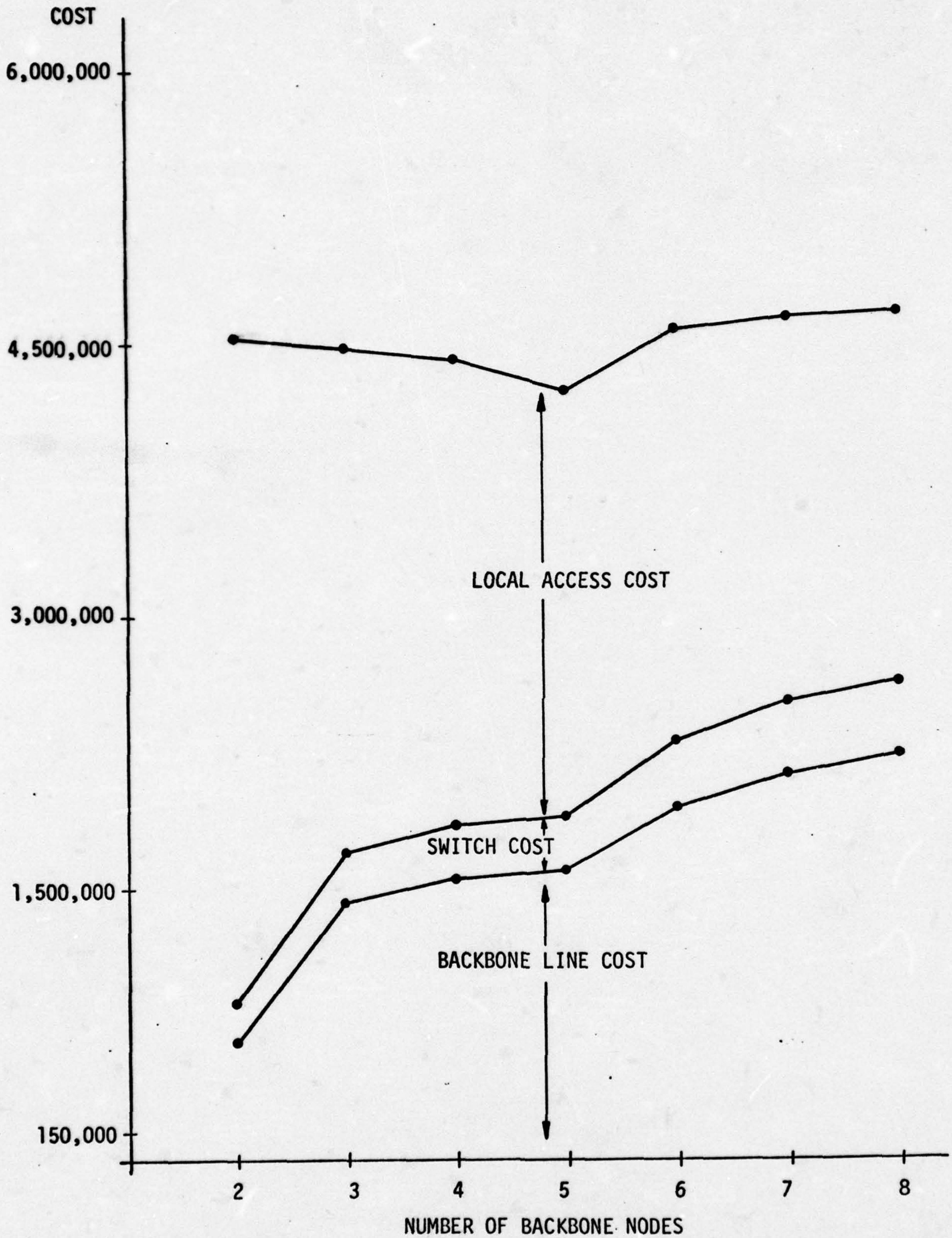

FIGURE 14: TRAFFIC - 100 TIMES
HARDWARE COST - 1/5

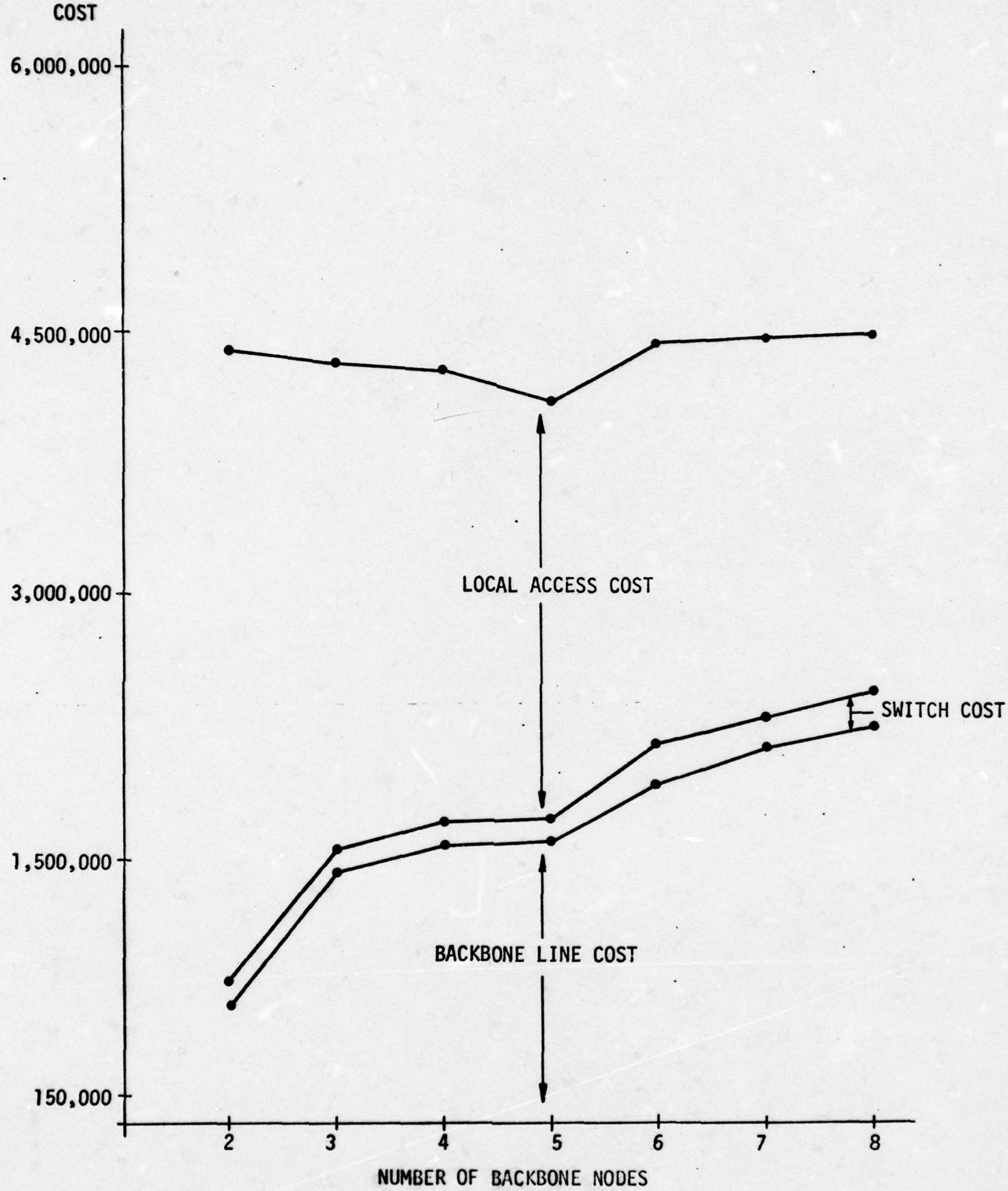

FIGURE 15: TRAFFIC - 100 TIMES
HARDWARE COST - 1/10

Traffic-nominal Hardware Cost-nominal

# of BB	Original Net Cost.	Dual Homing Cost	Total Cost
2	278	56	334
3	266	11	277
4	259	6	265
5	255	6	261
6	263	6	269
7	267	5	272
8	272	4	276

TABLE:16

Traffic-nominal Hardware Cost-1/2

# of BB	Original Net Cost	Dual Homing Cost	Total Cost
2	260	76	335
3	251	56	307
4	243	34	277
5	235	20	255
6	240	14	254
7	241	11	252
8	244	4	248

TABLE:17

Traffic-nominal Hardware Cost-1/5

# of BB	Original Net Cost	Dual Homing Cost	Total Cost
2	223	83	306
3	231	77	308
4	228	62	290
5	220	53	273
6	226	14	240
7	225	11	236
8	228	4	232

TABLE:18

Traffic-nominal Hardware Cost-1/10

# of BB	Original Net Cost	Dual Homing Cost	Total Cost
2	217	83	300
3	225	75	300
4	219	80	299
5	213	57	270
6	221	59	280
7	221	48	269
8	222	4	226

TABLE:19

Note: Costs for all tables expressed in thousands of dollars.

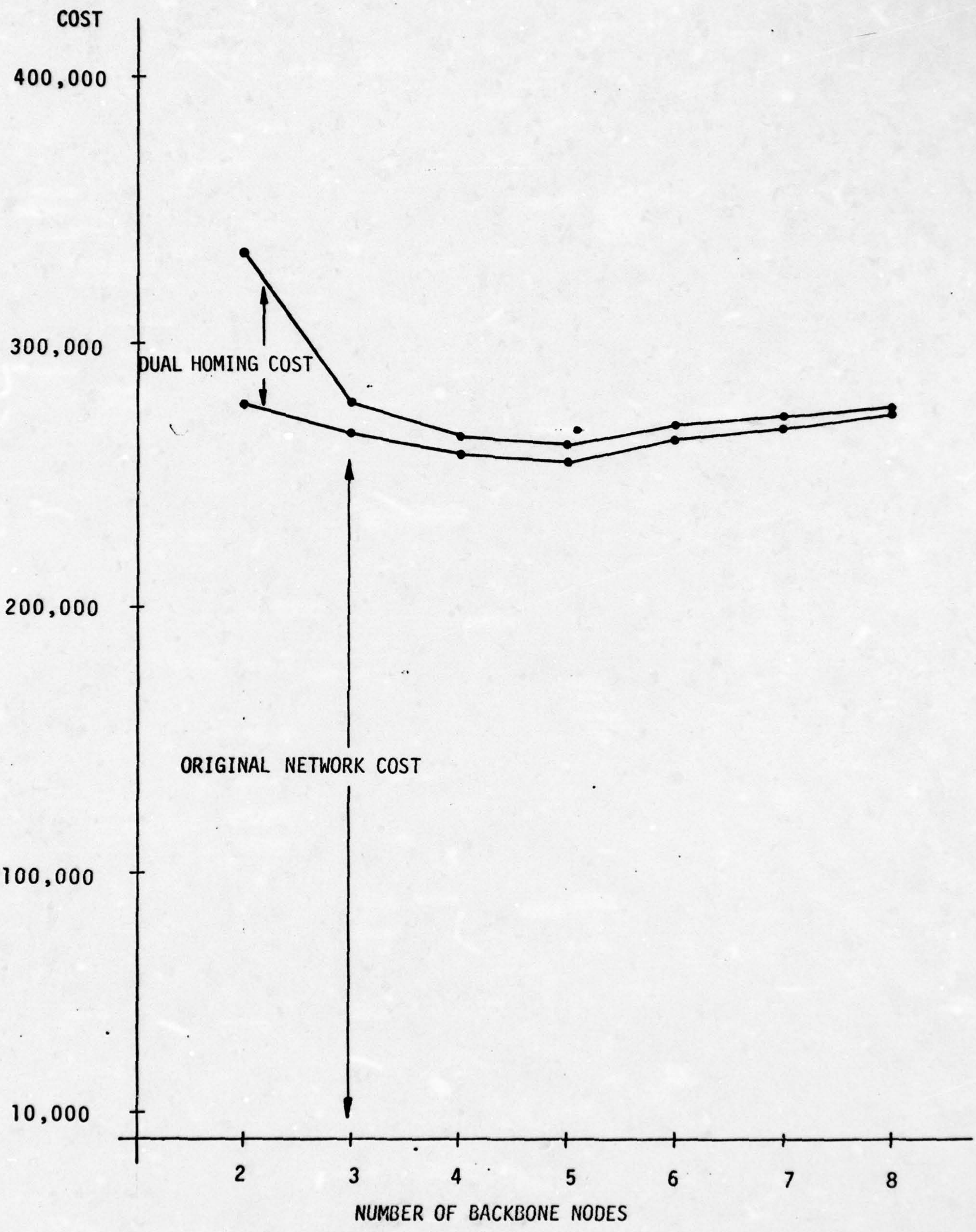

FIGURE 16: TRAFFIC - NOMINAL
HARDWARE COST - NOMINAL

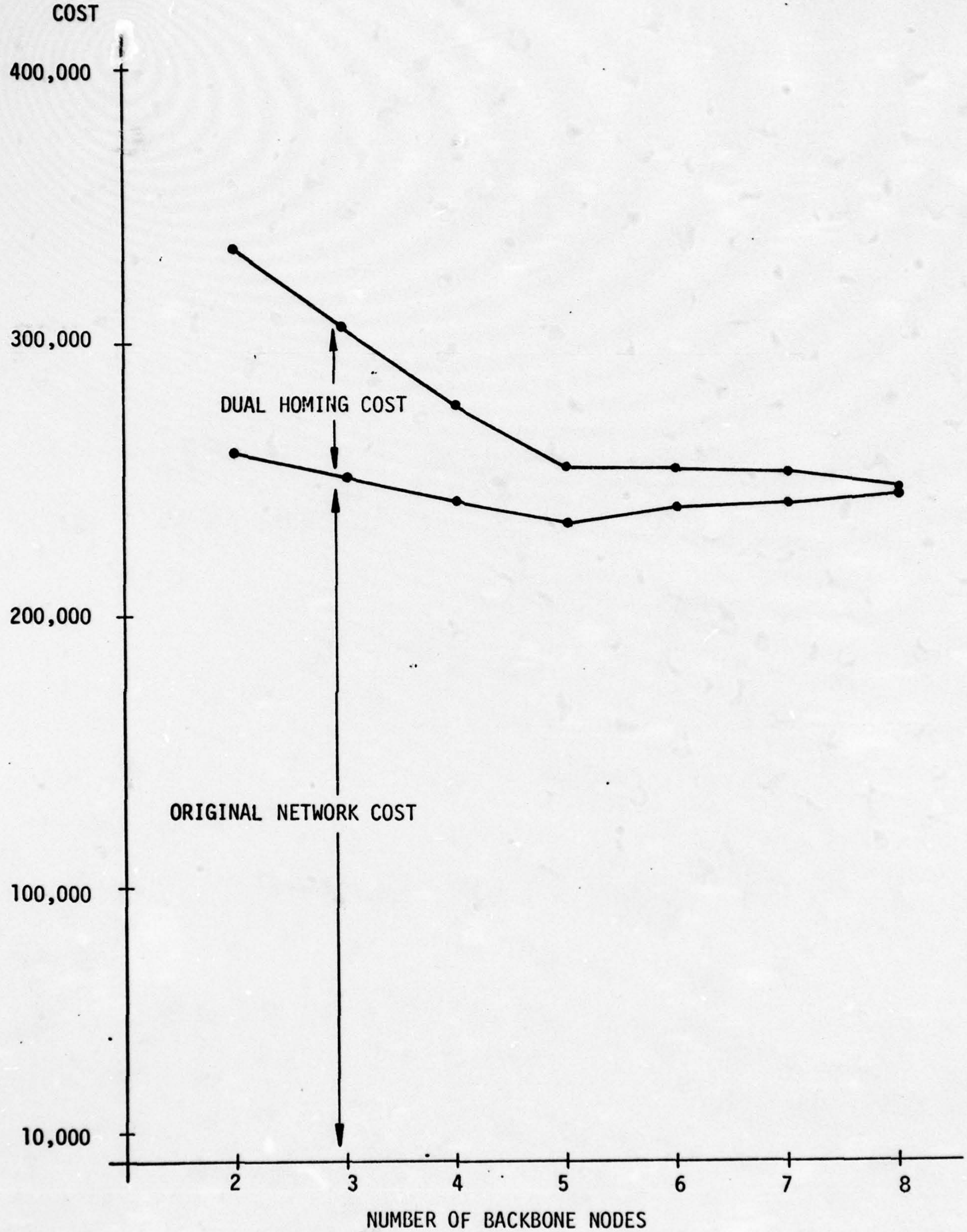

FIGURE 17: TRAFFIC - NOMINAL
HARDWARE COST - 1/2

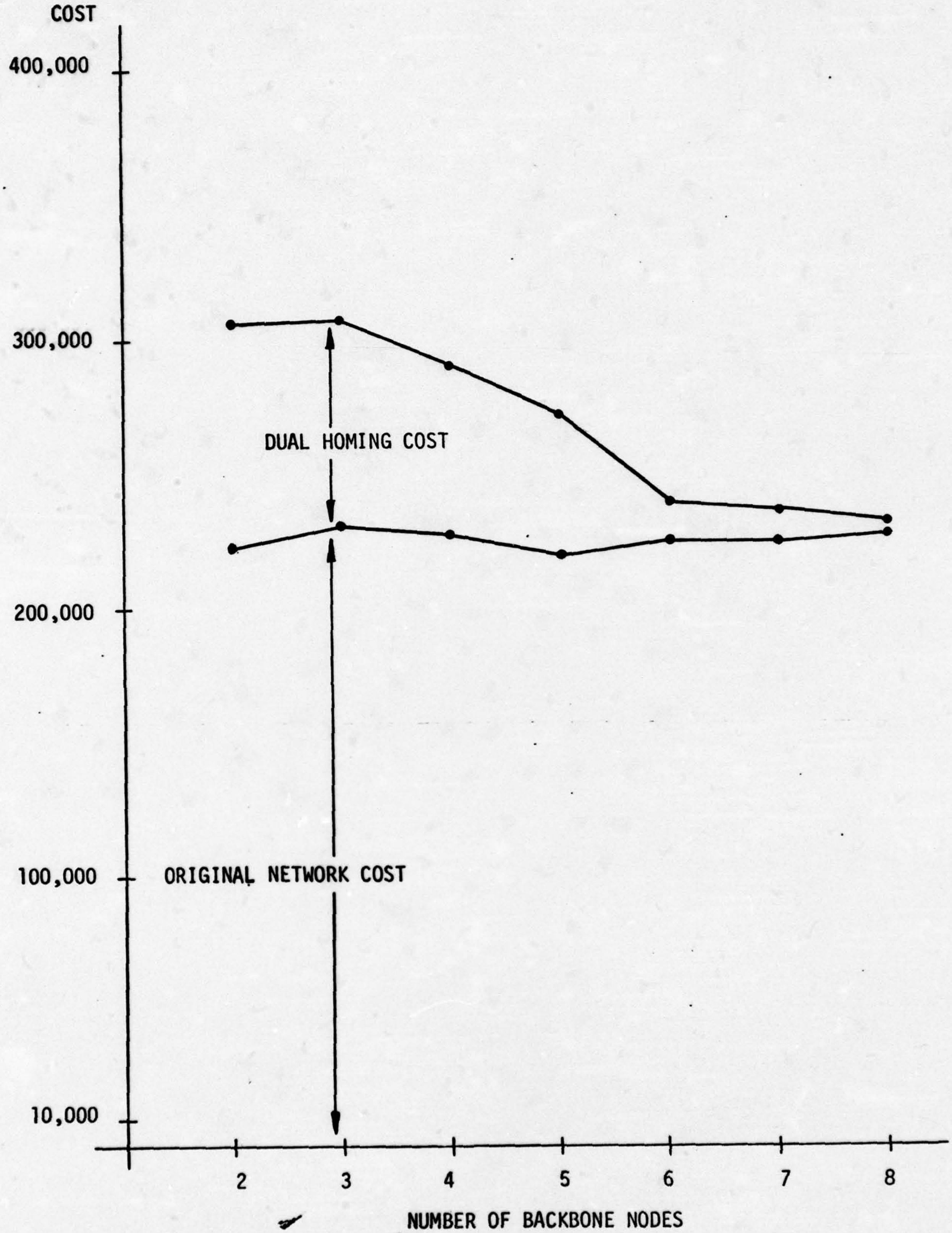

FIGURE 18: TRAFFIC - NOMINAL
HARDWARE COST- 1/5

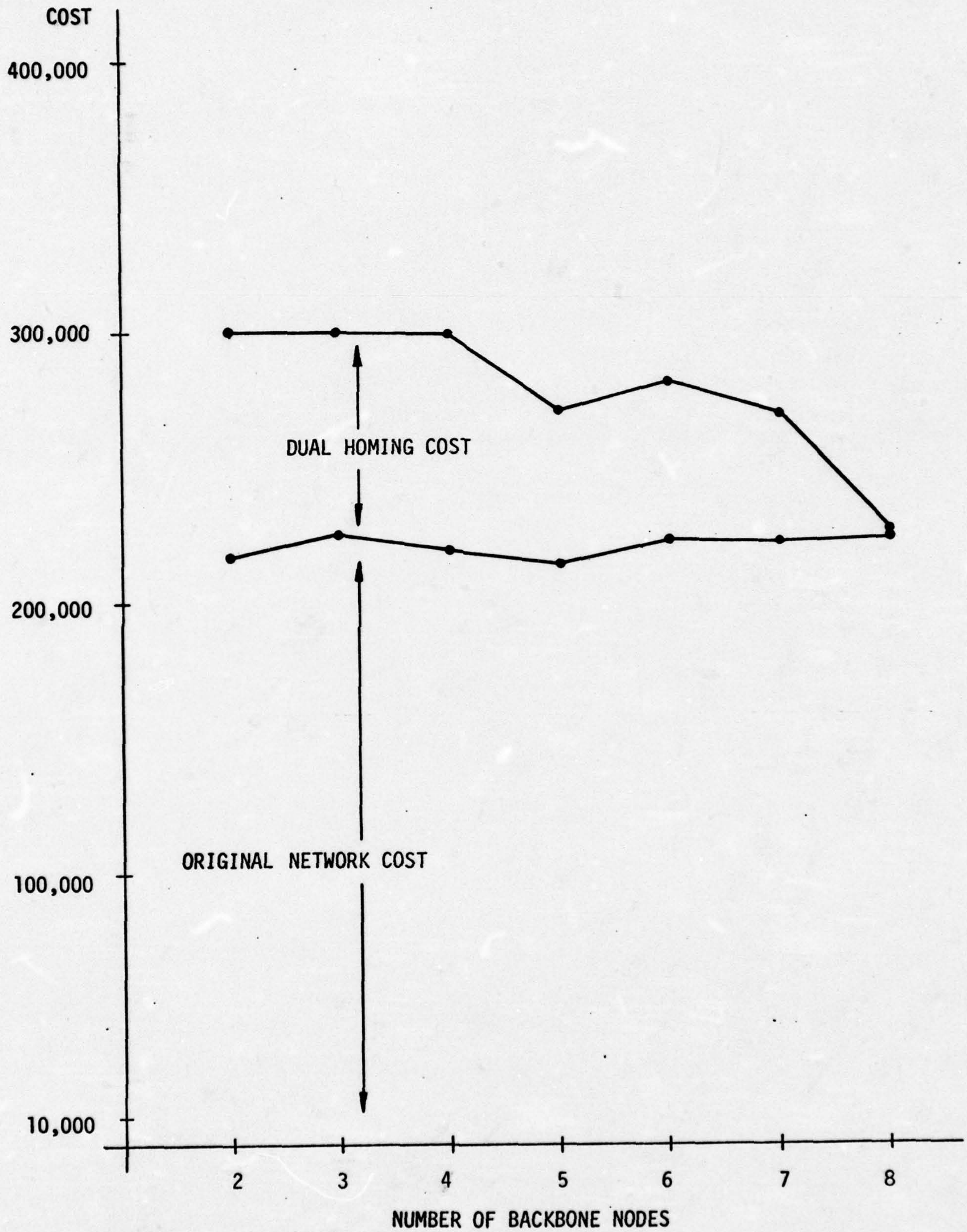

FIGURE 19: TRAFFIC - NOMINAL
HARDWARE COST - 1/10

All Satellite Backbone, Traffic - 10 times, Satellite Channel Cost - Nominal

# of BB	# of Channels (1.544 MBS)	Satellite Channel Cost	Ground Station Cost	Station Interface Cost	L.A. Cost	Total Cost
2	9	90	88	9	808	994
3	11	99	131	13	613	857
4	13	108	175	18	576	877
5	14	112	219	22	537	890
6	14	112	263	26	517	918
7	15	116	307	31	498	951
8	16	120	350	35	475	980

TABLE:20

All Satellite Backbone, Traffic - 10 times, Satellite Channel Cost - 1/2

# of BB	# of Channels (1.544 MBS)	Satellite Channel Cost	Ground Station Cost	Station Interface Cost	L.A. Cost	Total Cost
2	9	45	88	9	808	950
3	11	50	131	13	613	807
4	13	54	175	18	576	823
5	14	56	219	22	537	834
6	14	56	263	26	517	862
7	15	58	307	31	498	894
8	16	60	350	35	475	920

TABLE:21

Note: Costs for all tables expressed in thousands of dollars.

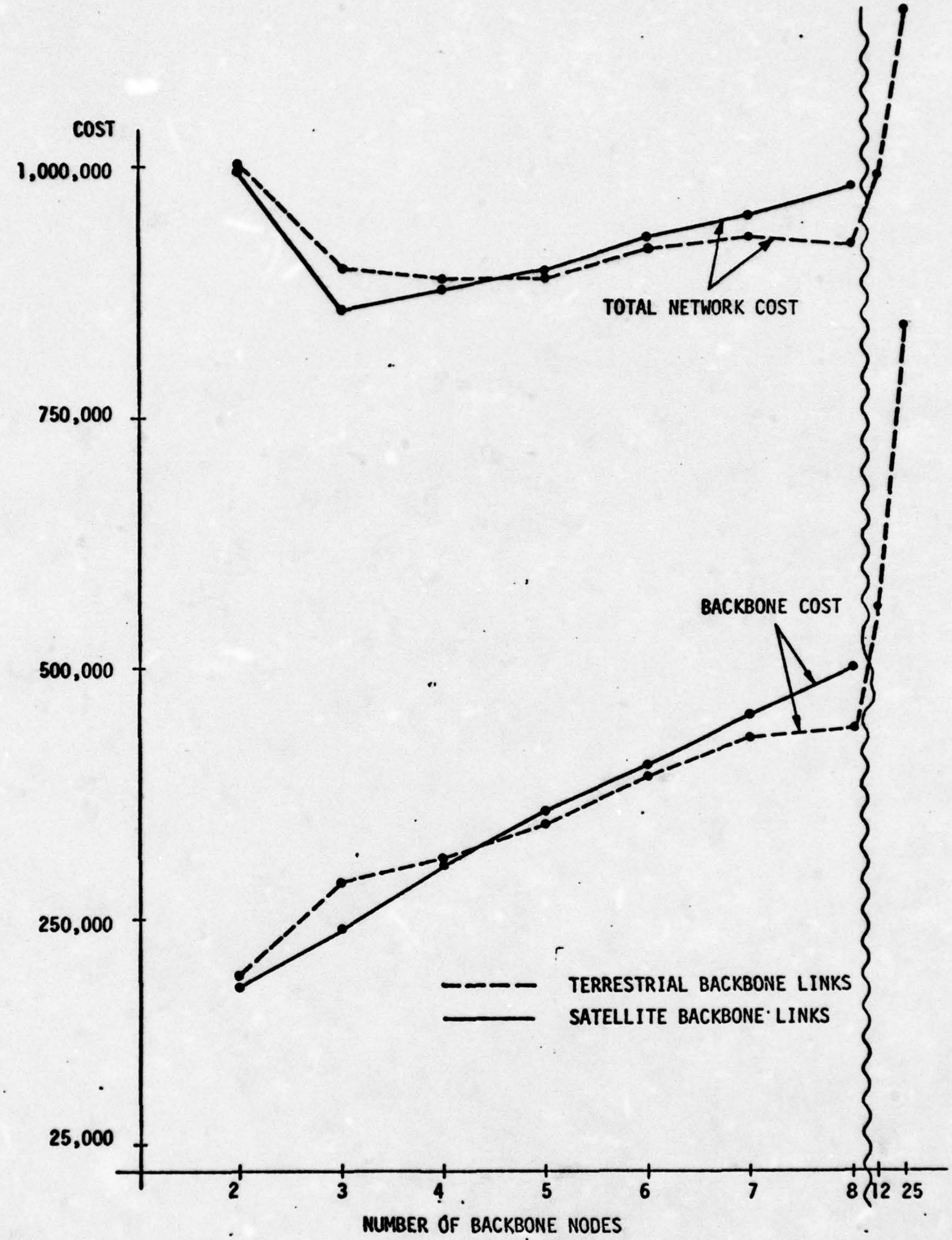

FIGURE 20: TRAFFIC - 10 TIMES
SATELLITE CHANNEL COST - NOMINAL

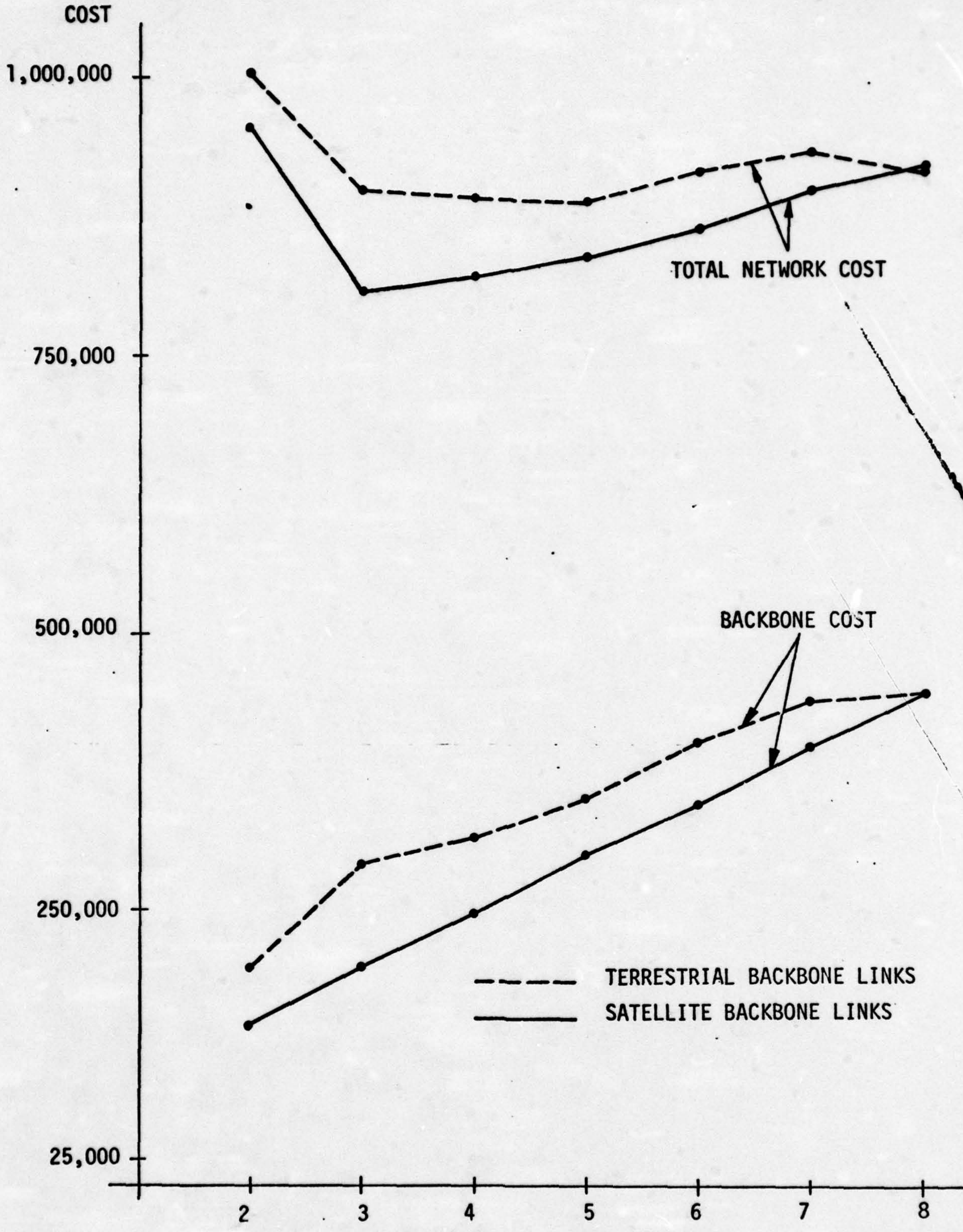

FIGURE 21: TRAFFIC - 10 TIMES
SATELLITE CHANNEL COST - 1/2

All Satellite Backbone, Traffic - 10 times, Satellite Channel Cost - 1/5

# of BB	# of Channels (1.544 MBS)	Satellite Channel Cost	Ground Station Cost	Station Interface Cost	L.A. Cost	Total Cost
2	9	18	88	9	808	923
3	11	20	131	13	613	777
4	13	22	175	18	576	791
5	14	22	219	22	537	800
6	14	22	263	26	517	828
7	15	23	307	31	498	859
8	16	24	350	35	475	884
12	21	28	526	53	426	1033
25	28	32	1095	110	337	1574

TABLE: 22

All Satellite Backbone, Traffic - 10 times, Satellite Channel Cost - 1/10

# of BB	# of Channels (1.544 MBS)	Satellite Channel Cost	Ground Station Cost	Station Interface Cost	L.A. Cost	Total Cost
2	9	9	88	9	808	914
3	11	10	131	13	613	767
4	13	11	175	18	576	780
5	14	11	219	22	537	789
6	14	11	263	26	517	817
7	15	12	307	31	498	848
8	16	12	350	35	475	872
12	21	14	526	53	426	1019
25	28	16	1095	110	337	1558

TABLE: 23

Note: Costs for all tables expressed in thousands of dollars.

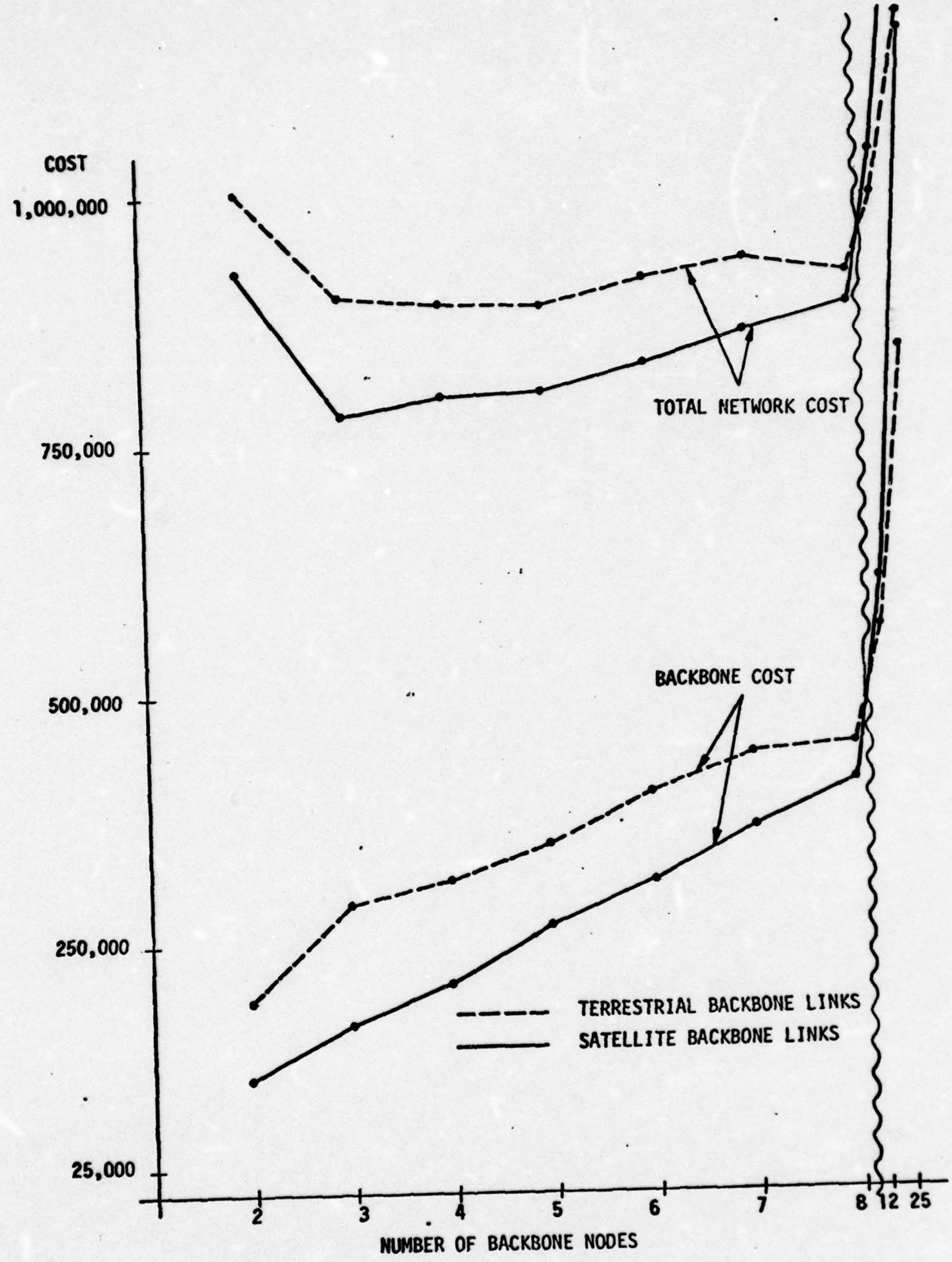

FIGURE 22: TRAFFIC - 10 TIMES
SATELLITE CHANNEL COST - 1/5

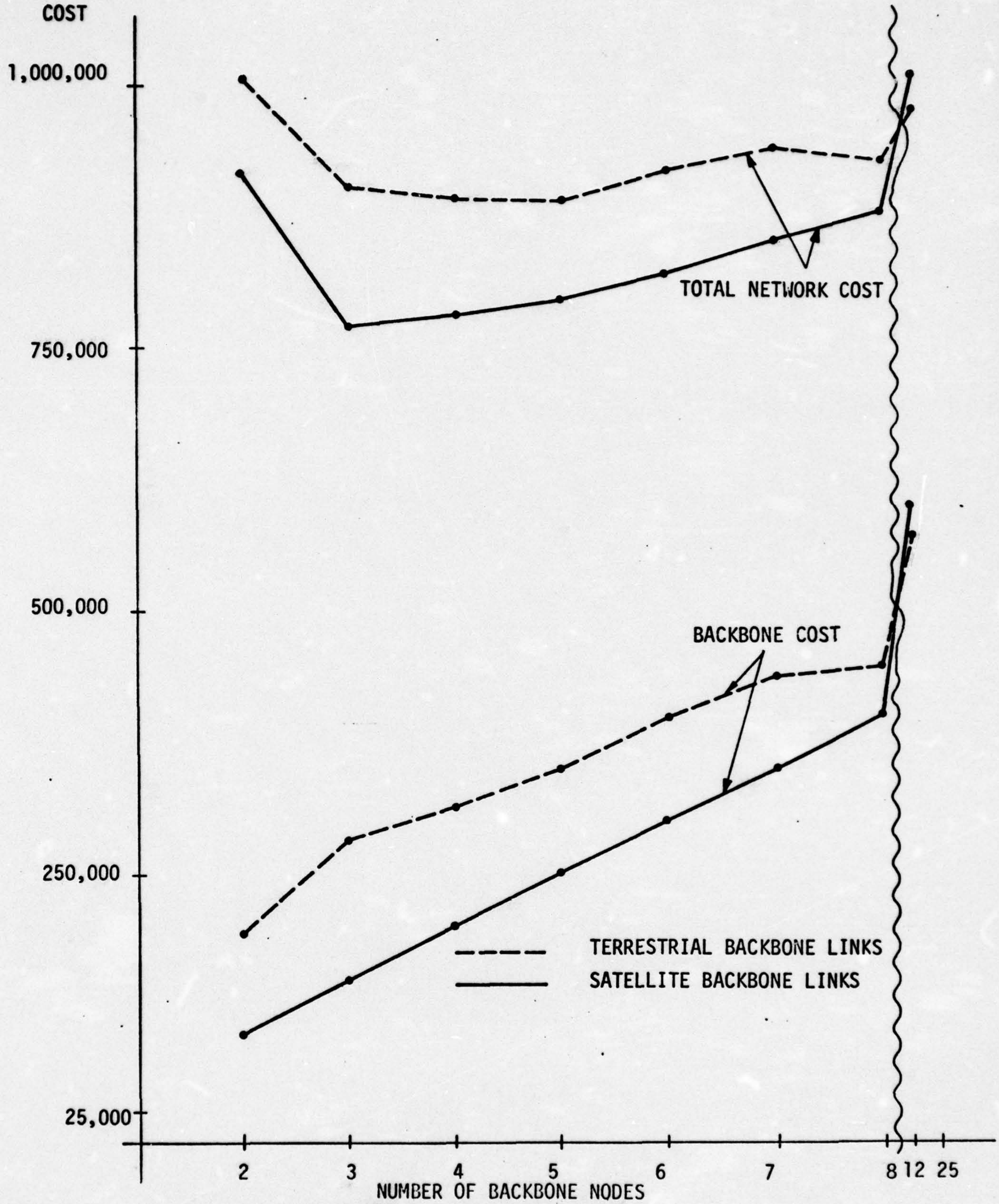

FIGURE 23: TRAFFIC - 10 TIMES
SATELLITE CHANNEL COST - 1/10

All Satellite Backbone
Traffic - 10 times nominal
Satellite Channel Cost - 1/2
Hardware and Ground Station Cost - 1/2

# of BB	# of Channels (1.544 MBS)	Satellite Channel Cost	Ground Station Cost	Station Interface Cost	L.A. Cost	Total Cost
2	9	45	44	5	808	902
3	11	50	66	7	613	736
4	13	54	87	9	576	726
5	14	56	109	11	537	713
6	14	56	131	13	517	717
7	15	58	153	16	498	725
8	16	60	175	18	475	728
12	21	70	263	26	426	785
25	28	80	548	55	337	1,020

TABLE: 24

All Satellite Backbone
Traffic - 10 times nominal
Satellite Channel Cost - 1/2
Hardware and Ground Station Cost - 1/5

# of BB	# of Channels (1.544 MBS)	Satellite Channel Cost	Ground Station Cost	Station Interface Cost	L.A. Cost	Total Cost
2	9	45	18	2	808	873
3	11	50	26	3	608	687
4	13	54	35	4	576	669
5	14	56	44	4	537	641
6	14	56	53	5	517	631
7	15	58	61	6	498	623
8	16	60	70	7	475	612
12	21	70	105	11	426	612
25	28	80	219	22	337	658

TABLE: 25

Note: Costs for all tables expressed in thousands of dollars.

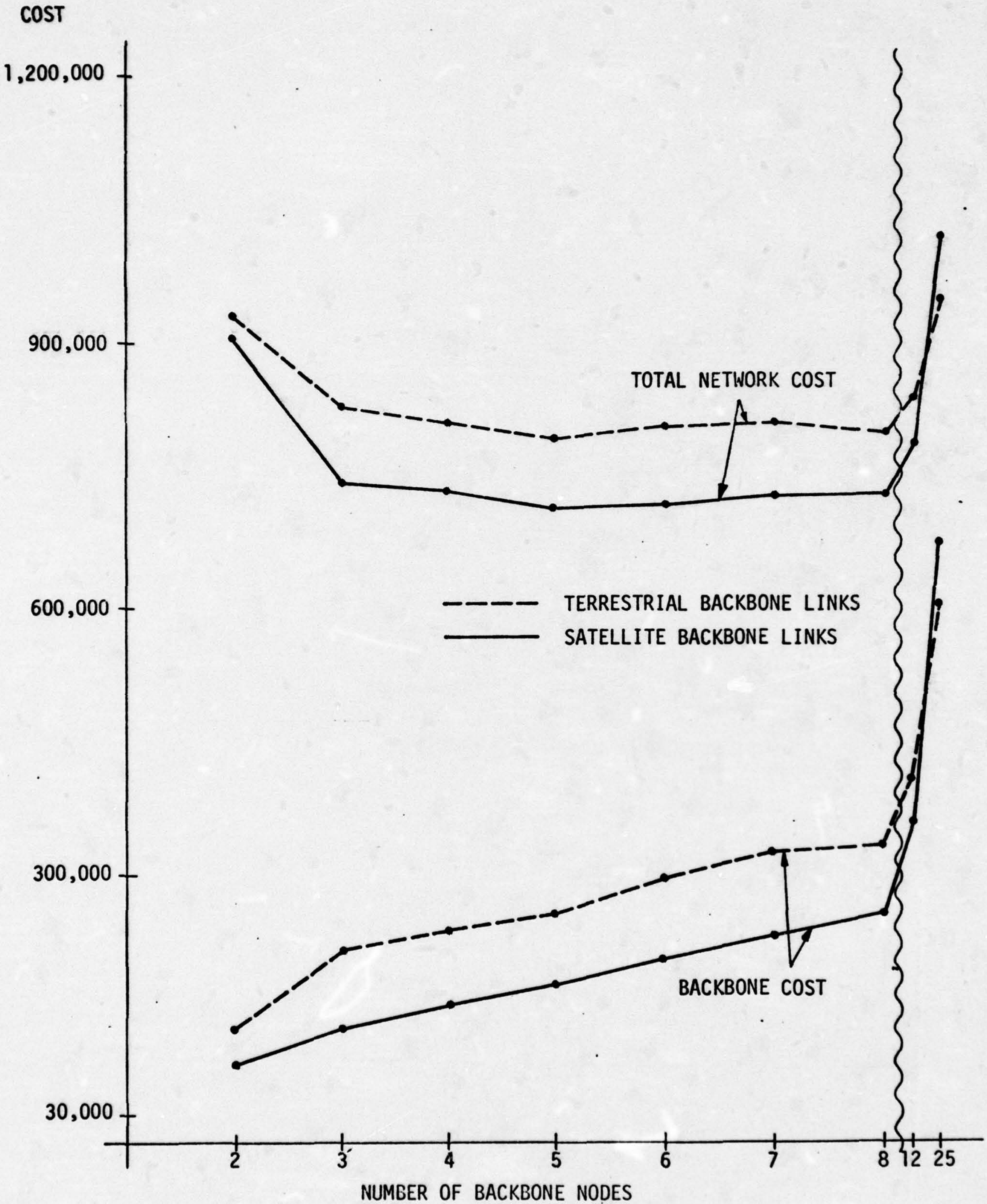

FIGURE 24: TRAFFIC - 10 TIMES
SATELLITE CHANNEL COST - 1/2
HARDWARE & GROUND STATION COST - 1/2

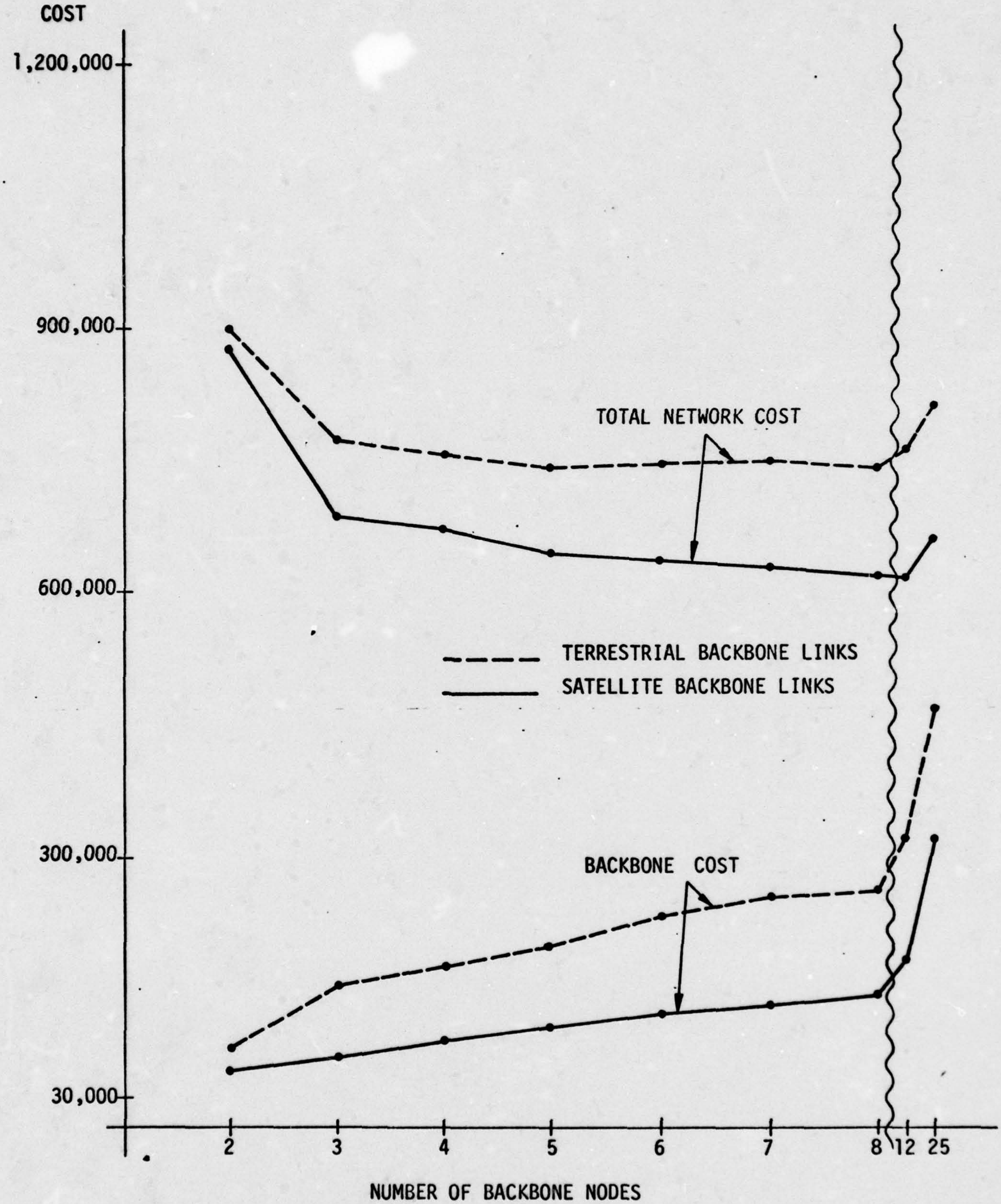

FIGURE 25: TRAFFIC - 10 TIMES

SATELLITE CHANNEL COST - 1/2

HARDWARE & GROUND STATION COST - 1/5

All Satellite Backbone
Traffic - 10 times nominal
Satellite Channel Cost - 1/2
Hardware and Ground Station Cost - 1/10

# of BB	# of Channels (1.544 MBS)	Satellite Channel Cost	Ground Station Cost	Station Interface Cost	L.A. Cost	Total Cost
2	9	45	9	1	808	863
3	11	50	13	1	605	669
4	13	54	18	2	576	650
5	14	56	22	2	537	617
6	14	56	26	3	517	602
7	15	58	31	3	498	590
8	16	60	35	4	475	574
12	21	70	53	5	426	554
25	28	80	110	11	337	538

TABLE: 26

Note: Costs for all tables expressed in thousands of dollars.

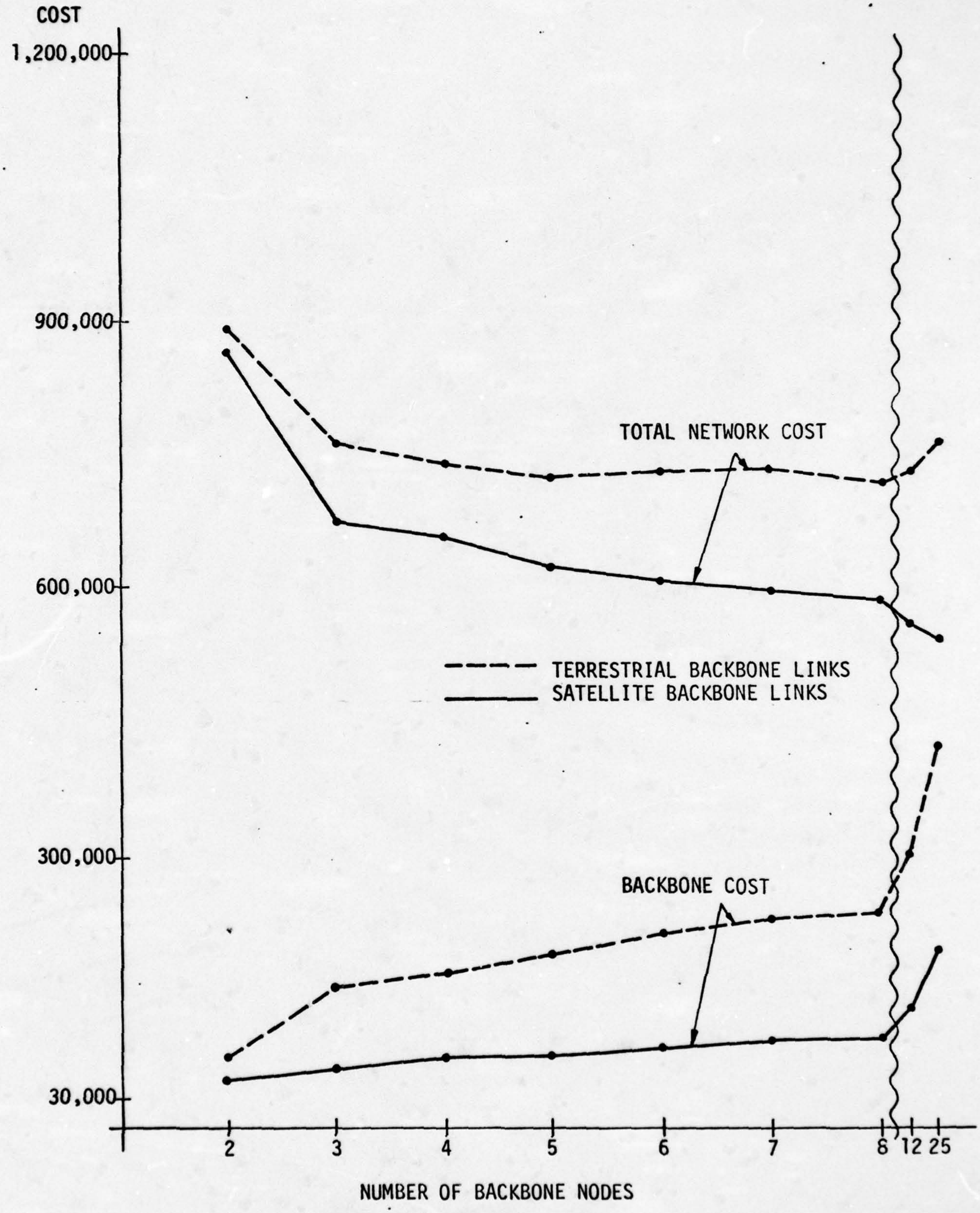

FIGURE 26: TRAFFIC - 10 TIMES
SATELLITE CHANNEL COST - 1/2
HARDWARE & GROUND STATION COST - 1/10

Satellite Connectivity, 5 BB nodes, Traffic - 10 times

# of Ground Stations	# of Channels (1.544 MBS)	Satellite Channel & Line Costs	Ground Station Cost	BB Interface Cost	Total Cost (BB only)
0	/	167	/	179	346
2	5	212	88	22	322
3	9	184	131	22	338
4	10	168	175	22	365
5	14	112	219	22	353

TABLE 27a

Satellite and Terrestrial Connectivity, 5 BB nodes, Traffic - 10 times

# of Ground Stations	# of Channels (1.544 MBS)	Satellite Channel & Line Costs	Ground Station Cost	Switch Cost	Total Cost (BB only)
0	/	167	/	179	346
2	9	208	88	173	469
3	9	184	131	183	499
4	11	138	175	167	480
5	14	128	219	161	508

TABLE 27b

Note: Costs for all tables expressed in thousands of dollars.

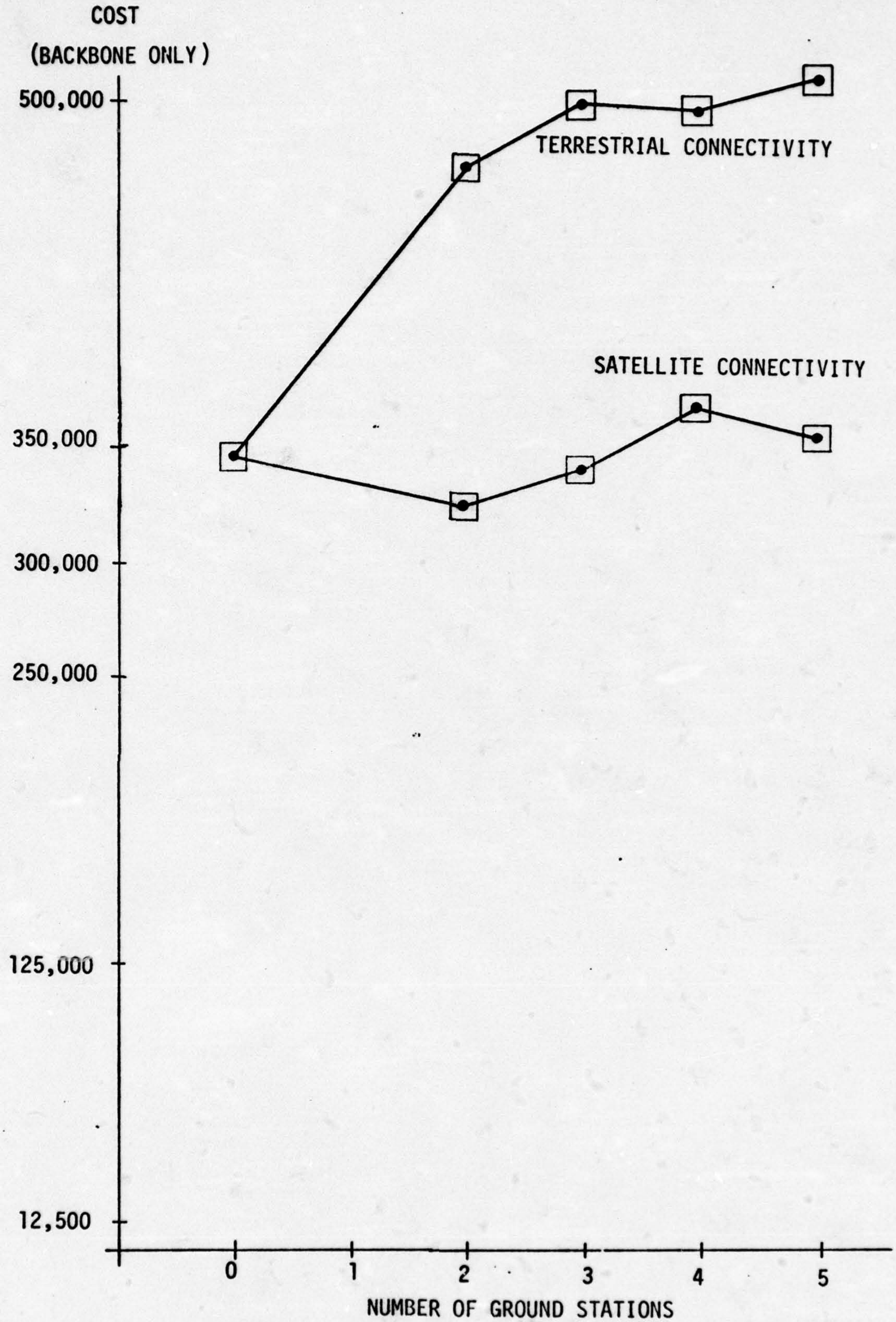

FIGURE 27: 5 NODE BACKBONE NETWORK WITH DIFFERENT NUMBERS OF GROUND STATIONS

Traffic - 100 times Hardware Cost - nominal W 6 MBS lines

# of BB	BB Line Cost	Switch Cost	L.A. Cost	Total Cost
2	343	1,205	3,620	5,168
3	711	1,335	2,790	4,836
4	774	1,464	2,588	4,826
5	828	1,515	2,349	4,692
6	901	1,810	2,272	4,983
7	957	1,915	2,131	5,003
8	992	1,947	2,040	4,979
12	1,276	2,436	1,694	5,406
25	1,756	3,703	1,332	6,791

TABLE: 28

Traffic - 100 times Hardware Cost - 1/2 W 6 MBS lines

# of BB	BB Line Cost	Switch Cost	L.A. Cost	Total Cost
2	343	602	3,620	4,565
3	711	668	2,790	4,169
4	774	732	2,588	4,094
5	828	757	2,349	3,934
6	901	905	2,272	4,078
7	957	958	2,131	4,046
8	992	974	2,040	4,006
12	1,276	1,218	1,694	4,188
25	1,756	1,852	1,332	4,940

TABLE: 29

Note: Costs for all tables expressed in thousands of dollars.

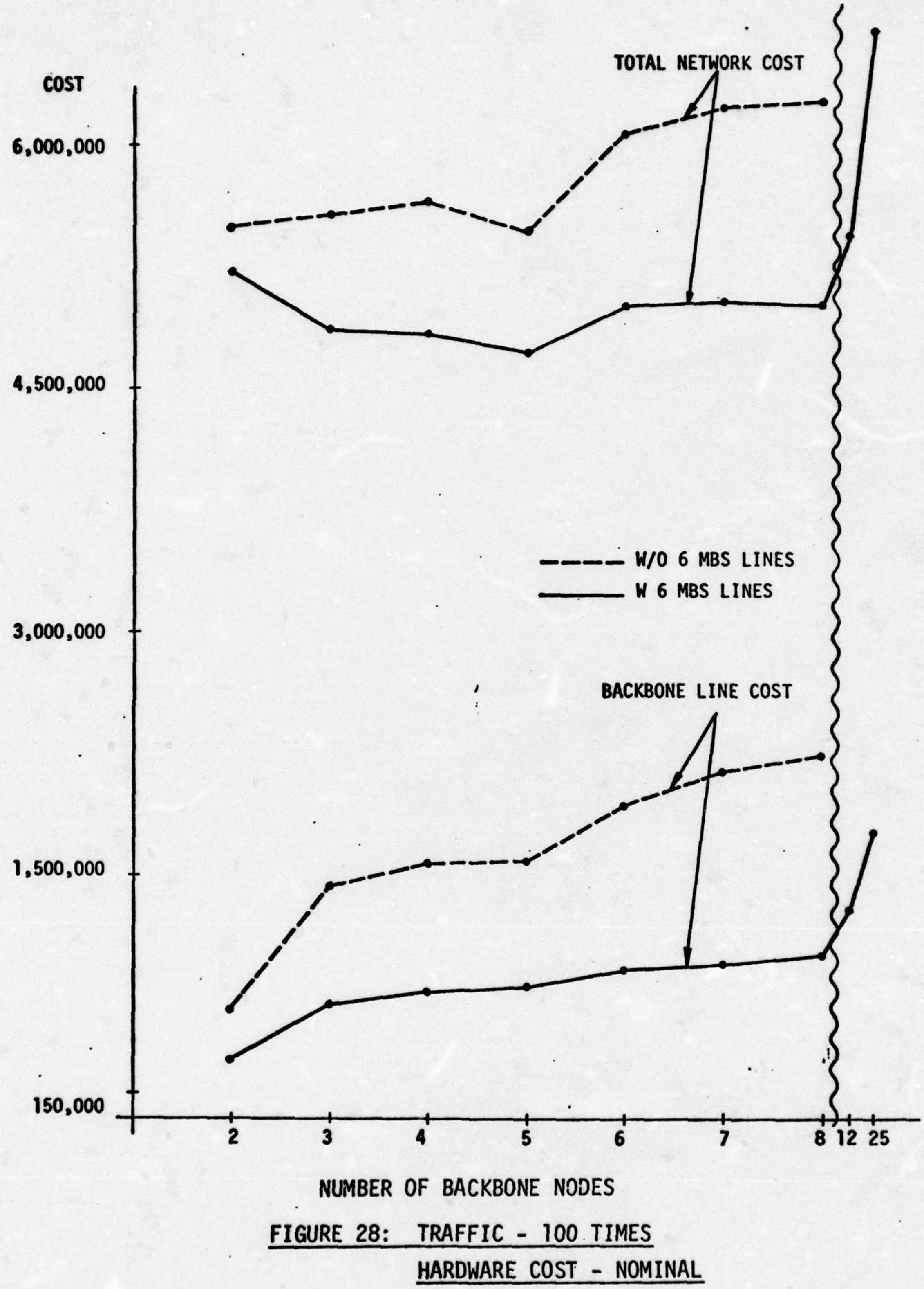

FIGURE 28: TRAFFIC - 100 TIMES
HARDWARE COST - NOMINAL
W 6 MBS LINES

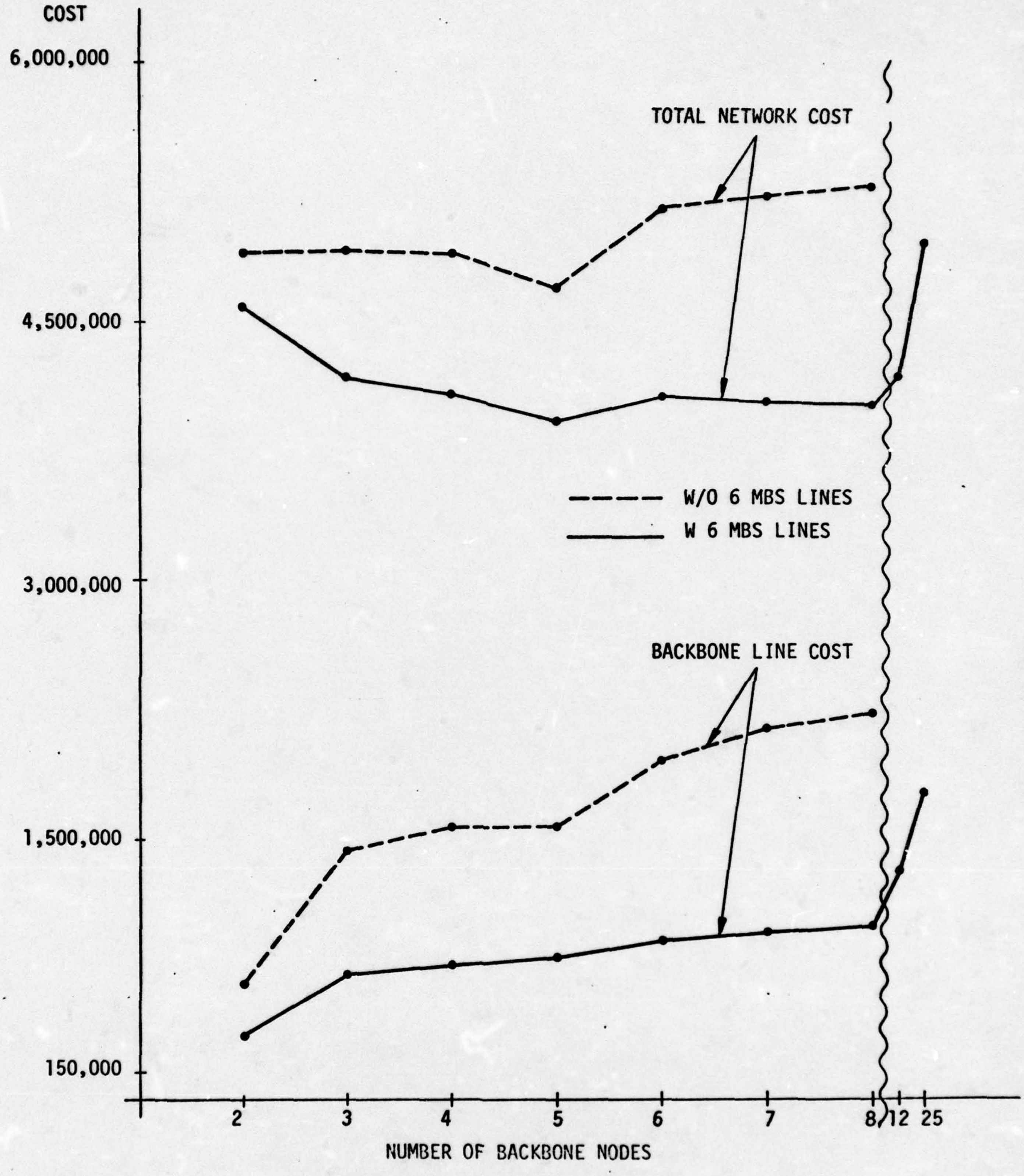

FIGURE 29: TRAFFIC - 100 TIMES
HARDWARE COST - 1/10

W 6 MBS LINES

Traffic - 100 times Hardware Cost - 1/5 W 6 MBS lines

# of BB	BB Line Cost	Switch Cost	L.A. Cost	Total Cost
2	343	241	3,620	4,204
3	711	267	2,790	3,768
4	774	293	2,588	3,655
5	828	303	2,349	3,480
6	901	362	2,272	3,535
7	957	383	2,131	3,471
8	992	389	2,040	3,421
12	1,276	487	1,694	3,457
25	1,756	741	1,332	3,829

TABLE: 30

Traffic - 100 times Hardware Cost - 1/10 W 6 MBS lines

# of BB	BB Line Cost	Switch Cost	L.A. Cost	Total Cost
2	343	120	3,620	4,083
3	711	134	2,790	3,635
4	774	146	2,588	3,508
5	828	152	2,349	3,329
6	901	181	2,272	3,354
7	957	192	2,131	3,280
8	992	195	2,040	3,227
12	1,276	244	1,694	3,214
25	1,756	370	1,332	3,458

TABLE: 31

Note: Costs for all tables expressed in thousands of dollars.

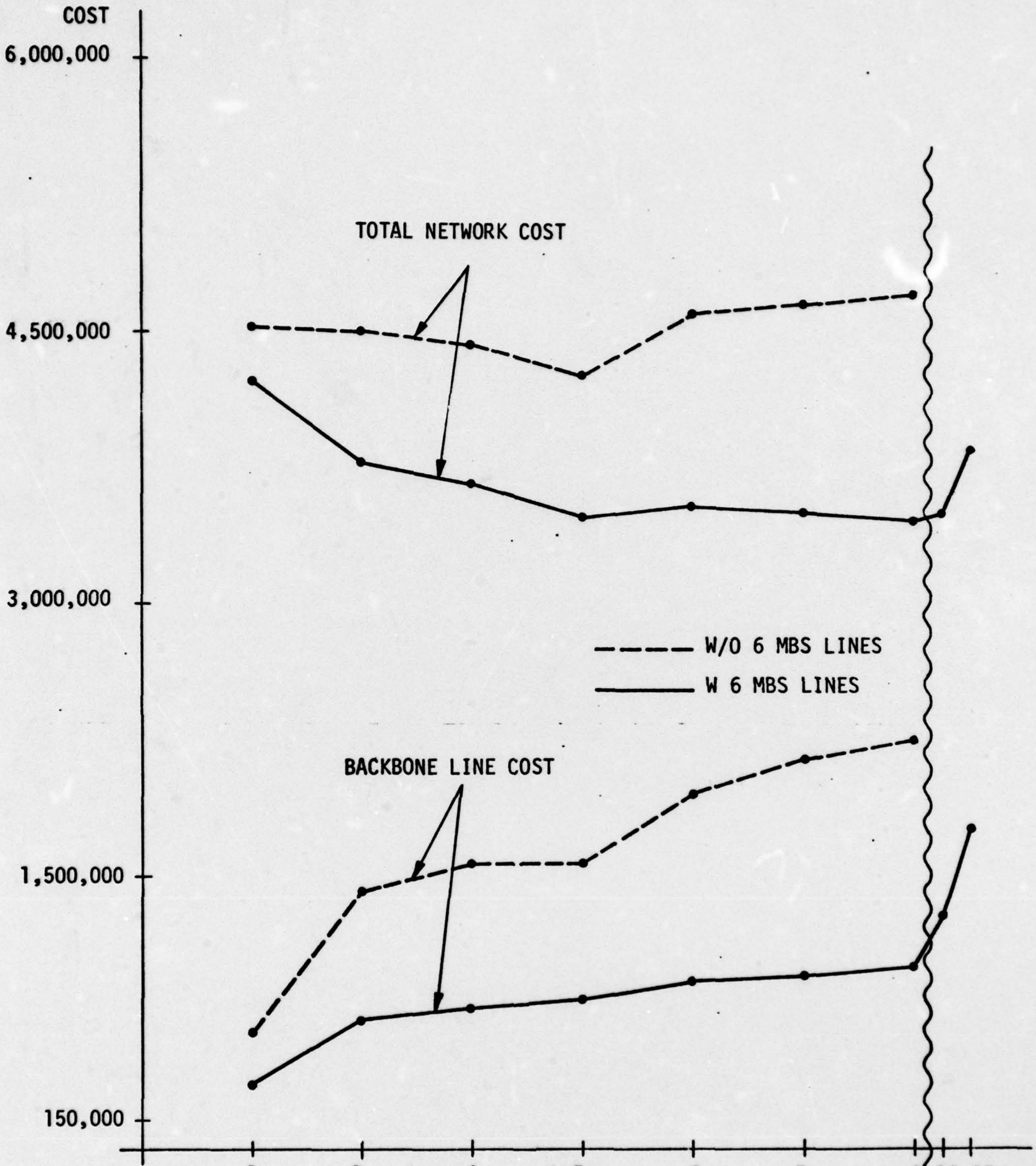

FIGURE 30: TRAFFIC - 100 TIMES
HARDWARE COST - 1/5
W 6 MBS LINES

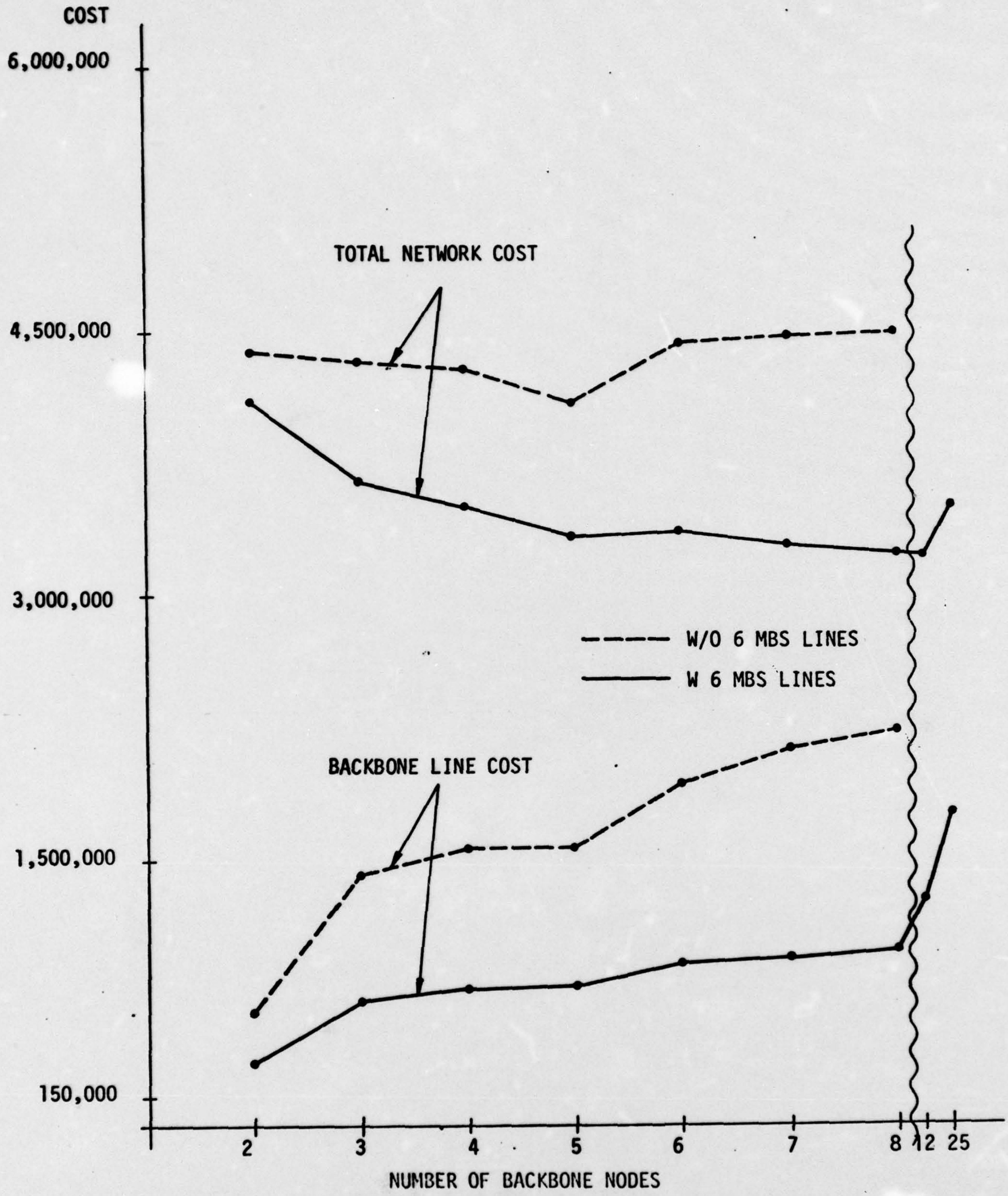

FIGURE 31: TRAFFIC - 100 TIMES
HARDWARE COST - 1/10
W 6 MBS LINES

5 BB nodes	Traffic - nominal
P_o	BB Line Cost
10	40
20	42
35	43
50	47
70	61
90	64

TABLE: 32

5 BB nodes	Traffic - 10 times
P_o	BB Line Cost
10	155
20	154
35	168
50	206
70	205
90	230

TABLE: 33

5 BB nodes	Traffic - 100 times
P_o	BB Line Cost
10	1,288
20	1,413
35	1,581
50	1,745
70	1,891
90	2,129

TABLE: 34

Note: Costs for all tables expressed in thousands of dollars.

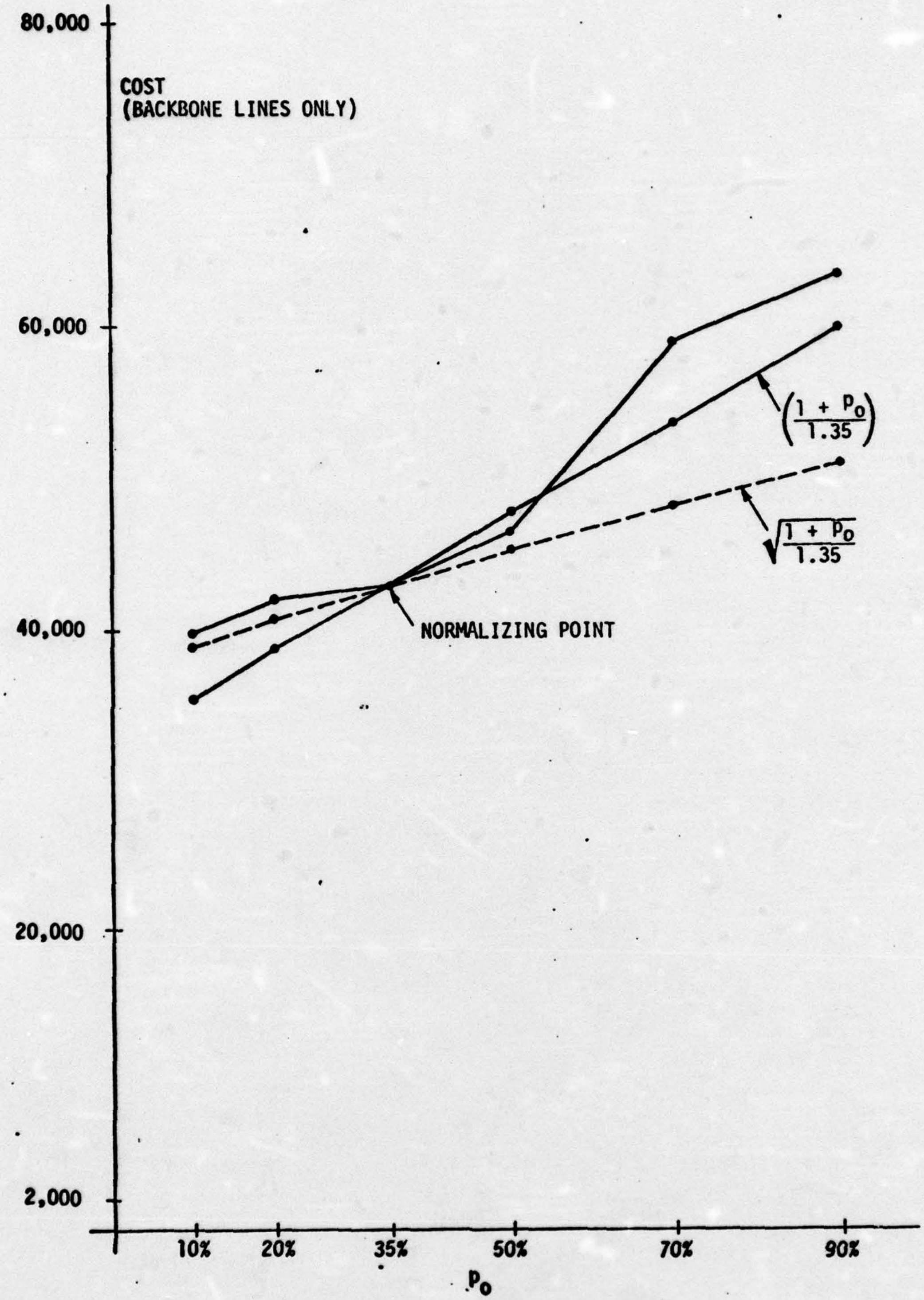

FIGURE 32: TRAFFIC - NOMINAL
5 BACKBONE NODES

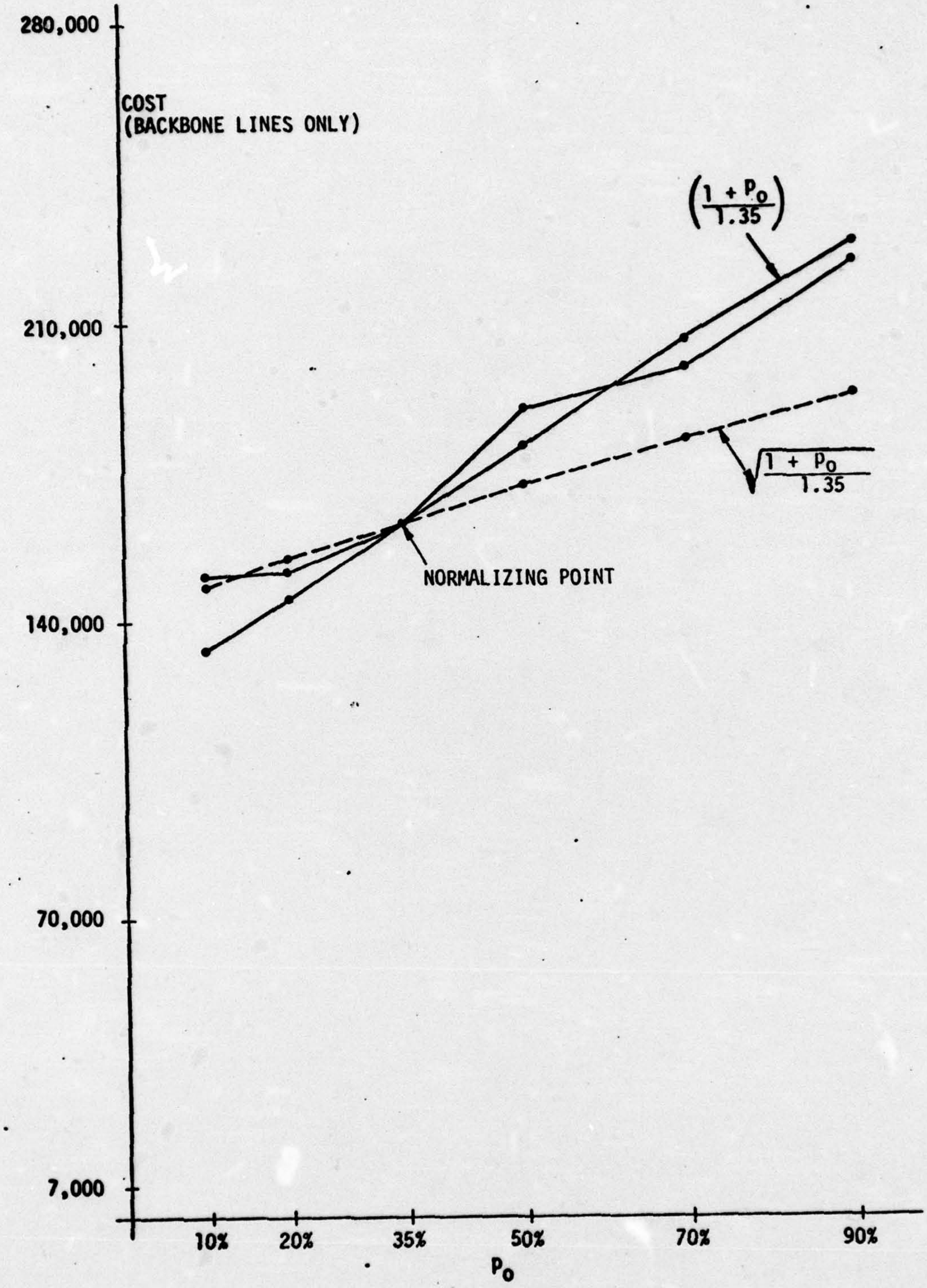

FIGURE 33: TRAFFIC - 10 TIMES
5 BACKBONE NODES

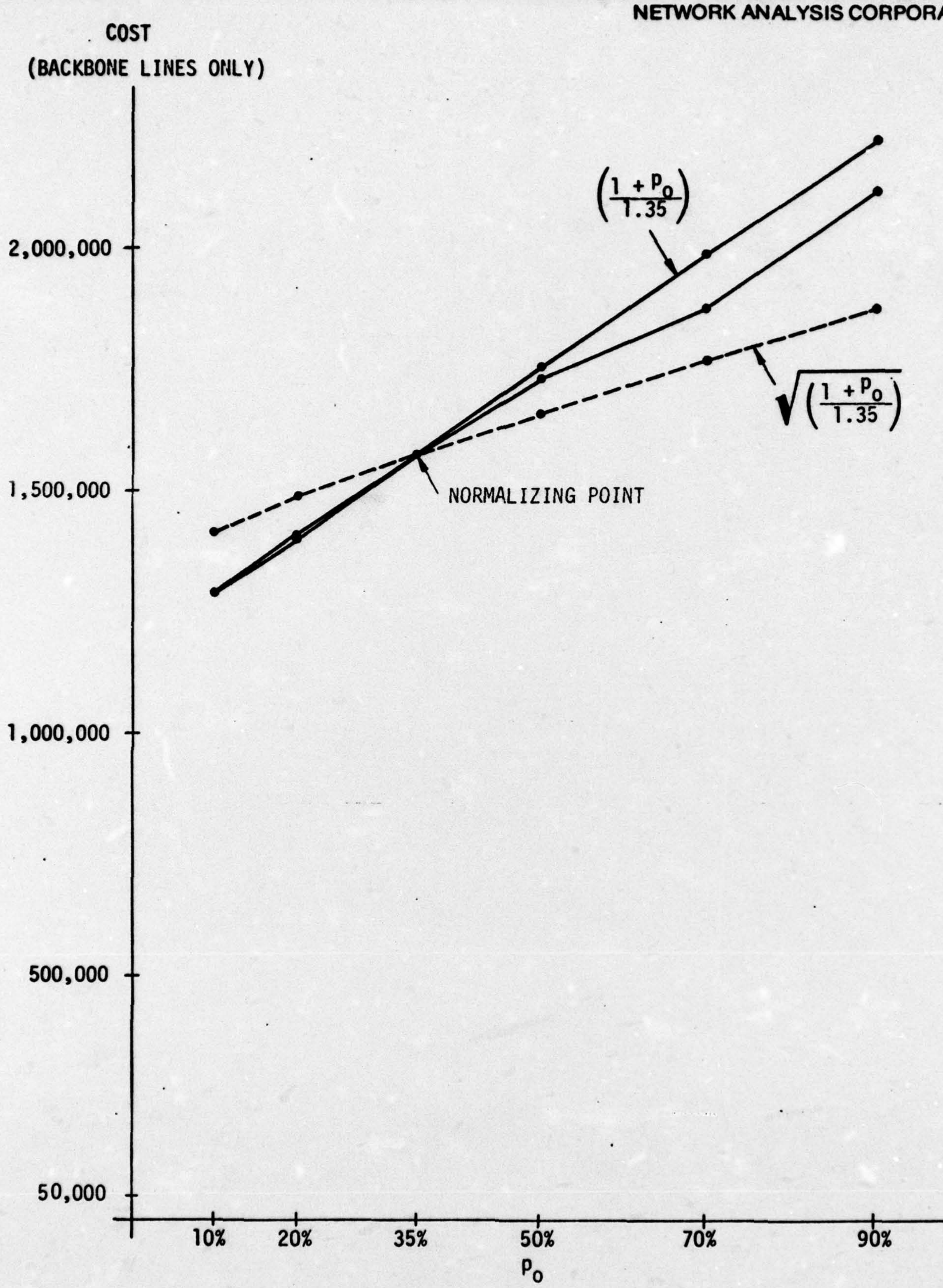

FIGURE 34: TRAFFIC - 100 TIMES
5 BACKBONE NODES

6.5. CONCLUSIONS

Tables 35 and 36 show the best network cost obtained and the number (or range, if precise number was not decidable from the study) of backbone nodes in the best terrestrial configuration. From these summary tables and the supporting data we can draw the following conclusions for the whole range of hardware cost scale factors.

1. Line costs are the dominant cost factor with local access costs dominating over backbone line costs. The only slight exceptions are:

   a. With traffic scaled 100 times and nominal hardware cost, the switch costs amounted to almost 30%.

   b. With traffic scaled 100 times and with more than 5 backbone nodes, the local access and backbone line costs became comparable.

2. From Table 35 we see that the network costs increase by a factor of about 3.4 when the traffic is scaled to 10 times nominal. This is primarily due to the square root (of 10) increase in line cost with bandwidth.

3. Again from Table 35 we see that network costs increase by a factor of 6 as traffic is scaled from 10 times nominal to 100 times nominal. This is due to several factors but primarily:

Traffic	Hardware Cost: Nominal	1/2	1/5	1/10
Nominal	255	235	220	213
10 times	883	793	739	712
100 times	5443	4686	4231	4080
100 times (w 6 MBS lines)	4692	4006	3421	3227

TABLE 35: TERRESTRIAL NETWORK COST

Traffic	Hardware Cost: Nominal	1/2	1/5	1/10
Nominal	5	5	5	5
10 times	4-5	5	5-6	5-12
100 times	2-5	5	5	5
100 times (w 6 MBS lines)	5	4-8	8-	8-

TABLE 36: OPTIMAL NUMBER OF BACKBONE NODES

Note: Costs for all tables expressed in thousands of dollars.

a. Switch costs are becoming a more significant factor and we have assumed a portion of the switch cost to vary linearly with throughput.

b. To obtain the needed large line capacities, the links often required multiples of 1.544 MBS channels. Since this capacity is the largest assumed available terrestrial option, increases in bandwidth have a linear dependence on bandwidth when such multiples are required. In effect, we have situations that exceed the range of bandwidth economies of scale. Under current tariffs this point begins at lower bandwidths than we modeled under our line cost formulation. Nonetheless, extending the range of square root economies of scale from 1.544 MBS to 6.176 MBS reduced the cost factor increase of the second 10 times traffic increase to the 4 to 5 range.

4. In all cases, the first few switches introduced sharply reduced costs by making a favorable tradeoff between reduced local access costs and backbone line costs. This is usually followed by a flat portion of the total network cost curve as this favorable tradeoff is ameliorated by an increasing switch cost component. As more switches are introduced a point is reached where decreasing local access costs and increasing backbone line costs cancel out and the increasing switch cost componentmakes these networks uneconomical. Decreasing the hardware cost factor extended the flat portion

to the right (more switches). The use of concentrators in the local access area extended the flat portion to the left (fewer switches) particularly at the nominal traffic levels. Each of these last two factors also reduced the slope of the "rise" at the respective ends of the flat region.

5. In all cases, reducing the hardware cost scale factor suppressed the right-hand rise from the flat portion - reducing the significance of switch cost. Because of the geographical idiosyncrasies of the distribution of military installations, 5 backbone nodes turned out to be a particularly good number of backbone nodes. Note in particular that at the 10 times nominal traffic level, there is only a small dependence on the correct selection of switch number. At the 1/10 hardware cost scale there was less than a 1% variation in total network cost for the range of 5-12 backbone nodes - an almost total lack of decision criticality for this traffic range and hardware cost! However, at the 180 MBS throughput level the optimal number of backbone nodes shifted back to the lower range, with 5 again emerging as the best choice independent of hardware cost. The best decision range is now in the region of a few - 5 or less - backbone nodes. Under the extended range of bandwidth economies, the optimum number of nodes shifted to the 8 or over region for most hardware cost scale factors.

An important conclusion is that providing a number of backbone nodes beyond a small region around five, is only economical for the

middle range of traffic (10 times nominal) and low hardware costs (1/10 nominal) unless strong bandwidth economies of scale continue to pertain as high as 6 MBS.

6. The costs of dual homing concentration points shifts the optimal region from around 5 backbone nodes to around 8 backbone nodes for the nominal traffic case. There is no other significant effect for the other traffic cases under our assumption of limited concentrator traffic handling ability.

We can draw the following conclusions from Tables and Figures 20-23 which compared pure satellite backbone networks with terrestrial backbone networks both at nominal hardware costs:

7. The optimum number of backbone nodes has shifted to a lower number (3 in this case) - the result of high earth station costs.

8. There is a cheaper design with all satellite backbone links than any design with all terrestrial backbone links - the result of high bandwidth concentration.

9. Each pure backbone network, terrestrial and satellite, has a distinct range of number of switches for which it is more economical.

10. With nominal earth station costs, even radical cost reductions (1/10) in satellite bandwidth did not dramatically affect total network cost or shift the optimum number of earth stations. The criticality of the number of earth stations did reduce and, of course, the relative advantage

of the satellite backbone over the terrestrial did increase. With the reduced satellite channel cost, the satellite backbone was cheaper for networks with fewer than 8 backbone nodes.

Figures and Tables 24-26 show the importance of earth station cost in network strategies.

11. With dropping earth station cost the satellite designs remained cheaper than terrestrial up to about 25 backbone nodes for 1/2 cost, to beyond 25 nodes for 1/5 cost, and for the 1/10 cost case (earth station cost is reduced to $100,000) the costs were still actually dropping at 25 nodes, indicating the merit of extending satellite access to the local access area.

From Figure and Table 27 we see that by redesigning the 5 backbone configuration allowing both satellite and terrestrial links we conclude:

12. Expectedly, cheaper networks result when the designer is not restricted to either satellite or terrestrial links. In this case the cheapest backbone network occurred with 2 ground stations (see lower curve of Figure 27) and 3 ground stations also resulted in a slightly cheaper network than either for the "pure" networks (the end points of the lower curve of Figure 27). Note that with 4 and 5 ground stations the best designs were more expensive than the pure terrestrial case.

13. The upper curve of Figure 27, when compared to the lower curve, demonstrates the high added cost of maintaining terrestrial connectivity is a mixed terrestrial/satellite network.

In Tables and Figures 28 to 31 we extended the range where the "square root" economies of scale with bandwidth apply to the 6.176 MBPS range and re-examined our design results.

14. Backbone line costs remain relatively flat for a greater range of backbone nodes making designs with 5-12 backbone nodes generally more attractive.

From Tables and Figures 32-34 we can observe:

15. The sensitivity of terrestrial backbone line cost to variations in p_o, the packet protocol overhead, is approximately proportional to the ratio of $(1 + p_o)/1.35$, where a p_o of 35% is used as a base index. Thus the cost of any terrestrial network design can be recosted with this approximation for any assumption on p_o. Recall that p_o may, in general, also affect the throughput cost coefficient of the switch cost.

This study was supported by a highly developed interactive software tool developed at NAC under ARPA sponsorship which allowed us to obtain well designed networks at reasonable computation cost as we varied a number of significant variables and options.

The most significant conclusion is that a relatively small number of backbone nodes (say, 5) appears to be the best strategy for a wide range of cost and traffic assumptions for packet-switched networks.

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13. ABSTRACT
New research results on the following major questions are reported: Results on integrated DOD Voice and Data Networks include: analytical models for determining blocking and delay on an integrated link and numerical investigation as a function of traffic and design variables; algorithms for integrated network design were developed and programmed. The program is capable of designing networks for voice traffic, signaling and data traffic. A circuit switch model for determining switch and network transit delays for circuit connection set-up was developed. A methodology for classification of telecommunications routing algorithms was developed. Results on topological gateway placement include an algorithm and program for interconnecting packet switched networks, studies of cost/performance tradeoffs, and an application to interconnect the ARPANET and AUTODIN II. In the packet radio area models were developed to estimate network initialization as a function of number of repeaters, transmission rates of repeaters and station, and operation disciplines. Finally, cost trends for large volume packet switched data networks are derived which incorporate switching and transmission costs, satellite and terrestrial channels and local distribution.

14. KEYWORDS - Computer networks, communication networks, terrestrial and satellite networks, packet radio networks, throughput, cost, delay, blocking, ARPA Computer Network, store-and-forward, packet switching, circuit switching, integrated switching, gateways.

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